Minnesota Power

Square Butte HVDC Upgrade

Facilities Study Report – MISO Project A727/A746/F118

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Revision History

Date	Rev	Description
04/25/2023	1.0	Initial Release

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Section 1: Project Overview

The purpose of this Facilities Study is to identify the scope, estimated cost, and timing of upgrades necessary on the existing Square Butte HVDC System in order to accommodate MISO Project F118, which is associated with Transmission Service Requests #90481026 & #95418167 (Project A727) and #91365462 (Project A746). To facilitate these Transmission Service Requests (TSRs), the existing Square Butte HVDC System would need to be modernized and its capacity would need to be increased by up to 350 MW to a total capability of 900 MW (the "HVDC Upgrade Project"). The HVDC Upgrade Project will consist of three general categories of upgrades:

1. **Converter Station Replacement** – Existing 550 MW converter stations interconnected to the AC transmission system at the Arrowhead and Square Butte East Substations will be replaced with increased capability to accommodate the TSRs. Both converter stations are 45+ years old and in need of modernization with or without the capacity increase. Minnesota Power, as the HVDC Owner, has determined that the converter station technology will also be changed from line commutated converter (LCC) to voltage source converter (VSC) technology, and that future expansion capability beyond 900 MW will be incorporated into the initial design of the new VSC HVDC converter stations.
2. **Transmission Line Modifications** – Modifications will be necessary to increase the capacity of the existing 465-mile HVDC transmission line in order to accommodate increased power flow associated with the TSRs.
3. **AC Interconnection Facilities** – The new VSC HVDC converter stations cannot be retrofitted into the existing converter station buildings, requiring that they be constructed on a new site nearby. Additional AC interconnection facilities must be constructed to re-connect the new converter stations to the existing transmission system near the existing points of interconnection.

The scope and estimated costs of these upgrades are discussed in subsequent sections of this report. The anticipated schedule for completing the upgrades is discussed in Section 6. The total anticipated cost of the HVDC Upgrade Project, along with the amount to be assigned to each TSR, is summarized in Table 1 below. Costs are presented in 2022 dollars.

HVDC 900 MW Upgrade *Project #A727 = 200 MW* *Project #A746 = 150 MW*	**Estimated Total HVDC Upgrade Project Cost**	**Amount Assigned to Project #A727**	**Amount Assigned to Project #A746**
Converter Station Replacement	$ 705,000,000	$ 165,000,000	$ 123,000,000
Interconnections to AC System	$ 115,000,000	$ 15,000,000	$ 11,000,000
Transmission Line Modification	$ 58,000,000	$ 25,000,000	$ 33,000,000
Internal & Professional Services	(Included)	(Included)	(Included)
TOTAL (2022 $)	**$ 878,000,000**	**$ 205,000,000**	**$ 167,000,000**

Table 1: HVDC Upgrade Project Cost Estimate Summary

Due to Minnesota Power's previously-identified need to modernize the Square Butte HVDC System and the additional future capacity considerations noted above, Minnesota Power is proposing to share in some of the costs associated with the modernization part of the HVDC Upgrade Project. Therefore, as shown in Table 1, the two TSRs (Projects A727 and A746) will each be assigned a portion of the total HVDC Upgrade Project costs and Minnesota Power will also bear a portion of the cost as the HVDC Owner. Cost estimates and cost assignment are discussed further in subsequent sections of this report. The costs assigned to Project A727 will be shared equally between the two 100 MW TSRs that are included in Project A727.

Section 2: Converter Station Replacement

2.1 Background

The Square Butte HVDC System has been delivering energy from the Center Converter Station in Center, North Dakota to the Arrowhead Converter Station in Duluth, Minnesota for over 45 years. These converter stations are connected by a 465 mile HVDC transmission line operating at ±250 kV. This HVDC line is capable of transferring up to 550 MW (1100 Amps) during bipole operation and up to 275 MW (1100 Amps) during single-pole operation utilizing metallic return or – in case of emergency – ground return.

Much of the existing equipment associated with the Square Butte HVDC converter stations is past its design life and Minnesota Power is beginning to see an impact on the reliability of the facility. Because of this impact, Minnesota Power had previously identified a need to modernize the Square Butte HVDC converter stations. This project has been reported for several years under MISO MTEP Project #4295.

To modernize the terminals of the existing Square Butte HVDC Line and implement the latest voltage source converter ("VSC") HVDC technology, new buildings and electrical infrastructure need to be constructed on a new site near the existing HVDC terminals. Due to the specialized nature of the technology, the new HVDC converter stations will be delivered as turnkey projects by the original equipment manufacturer ("OEM"). To execute this type of project, Minnesota Power will need to work with the HVDC OEM and an HVDC Owner's Engineer complete pre-specification studies and develop a detailed technical specification sufficient for the HVDC OEM to provide a firm-price proposal for an engineer-procure-construct ("EPC") contract.

2.2 Scope of Work

As noted above, Minnesota Power has a baseline need to replace the original HVDC converter stations with new converter stations implementing the latest and greatest in modern HVDC technology ("HVDC Modernization Project"). In order to achieve the capacity necessary to facilitate the TSRs being evaluated in MISO Project F118, the planned HVDC Modernization Project will need to be designed to facilitate at least 900 MW (1800 Amps) of capacity in the new converter stations, which is an increase of 350 MW over the present 550 MW rating of the facility. Minnesota Power, as the HVDC Owner, has additional interest in optimizing the long-term capacity potential of the HVDC line beyond what the TSR customers currently require and is electing to design the HVDC Modernization Project to provide 1500 MW (3000 Amps) of capacity in the new converter stations. This represents the highest VSC converter station capacity currently available in the market. While the initial operation of the new converter stations will be limited to 900 MW consistent with the needs of the existing capacity plus the new TSRs, the potential to operate up to 1500 MW after a future rebuild of the HVDC transmission line will also be available.

Minnesota Power has developed a flexible and expandable solution to meet near-term needs on the HVDC line will preserving the long-term capacity expansion opportunities noted above. As a result, the existing 550 MW ±250 kV bipole HVDC line will be converted to a symmetric monopole (SMP) configuration with one converter on each end rated for 525 kV and 1500 MW (3000 Amps) but initially operated at ±250 kV and 900 MW (1800 Amps). In coordination with the HVDC OEM, the converter stations will be designed for future expansion to operate as part of a 3000 MW ±525 kV bipole HVDC line. The post-project SMP configuration of the HVDC line is shown in Figure 1 below.

The scope of supply for the HVDC OEM will include both of the relocated converter stations, including valves, converter transformers, smoothing reactors, DC equipment, AC circuit breakers, control & protection, and all associated facilities. The new HVDC converter stations will be designed to interconnect at 345 kV on the AC system side, as further discussed in Section 4: AC Interconnection Facilities.

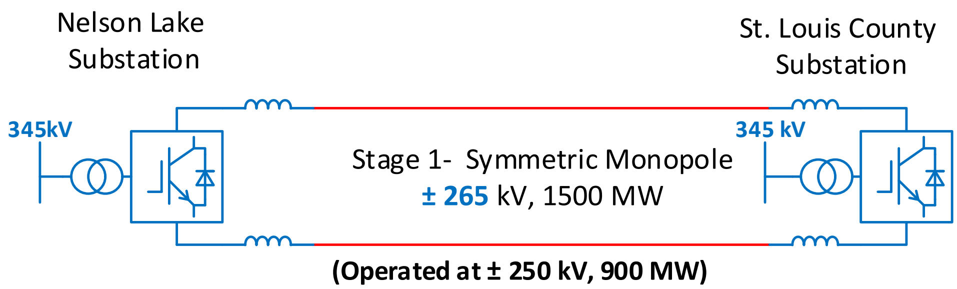

Figure 1: Post-Project HVDC Line Configuration

2.3 Cost Assignment

The anticipated costs of modernizing and upgrading the HVDC converter stations are shown in Table 2. Costs are presented in 2022 dollars. The initial converter station replacement base cost was developed from a budgetary estimate provided by the HVDC OEM. To maintain confidentiality of the OEM's direct budgetary estimate, Minnesota Power has added internal & professional services, AFUDC and contingency to the converter station base cost shown in Table 2. As discussed above, the HVDC converter station replacement will be a turnkey project and very little detailed design work was done prior to receiving the budgetary estimate from the HVDC OEM. If design assumptions change significantly during the development of the project, the base cost shown in Table 2 may change.

HVDC 900 MW Upgrade *Project #A727 = 200 MW* *Project #A746 = 150 MW*	Estimated Total Converter Station Upgrade Cost	Amount Assigned to Project #A727	Amount Assigned to Project #A746
Converter Station Base Cost	$ 705,000,000	$ 165,000,000	$ 123,000,000
Internal & Professional Services	(Included)	(Included)	(Included)
Contingency - Converter Station	(Included)	(Included)	(Included)
AFUDC - Converter Station	(Included)	(Included)	(Included)
TOTAL - Converter Stations	**$ 705,000,000**	**$ 165,000,000**	**$ 123,000,000**

Table 2: HVDC Upgrade Project – Converter Station Replacement Cost Breakdown

Due to Minnesota Power's previously-identified need to modernize the existing HVDC converter stations and the additional future capacity considerations included with the project, Minnesota Power is proposing to share in some of the converter station replacement costs. Therefore, as shown in Table 2, the two TSRs will each be responsible for a portion of the converter station replacement costs and Minnesota Power will also bear a portion of the cost.

Section 3: Transmission Line Modifications

3.1 Background

The Square Butte HVDC converter stations are connected by a 465 mile HVDC transmission line operating a ±250 kV. The HVDC transmission line is presently designed with capacity to carry up to 550 MW (1100 Amps) during bipole operation and up to 275 MW (1100 Amps) during single-pole operation utilizing either metallic return or – in case of emergency – ground return. There are three different conductors used over the 465-mile length of the HVDC transmission line. While the majority of the line consists of 2839 ACSR, smaller conductors are present in two areas. At the Missouri River crossing in North Dakota, there is a segment of 2607 ACSR. In a separate location also in North Dakota there is a short segment of 2312 ACSR, which is the most limiting transmission line conductor for facility ratings. All three of these conductors have been designed to have sufficient conductor-to-ground clearance at an operating temperature consistent with the present 550 MW transfer level according to Minnesota Power's facility ratings methodology.

3.2 Scope of Work

The existing HVDC transmission line is presently designed to operate continuously at 550 MW (1100 Amps). To achieve a higher continuous rating of 900 MW (1800 Amps), Table 3 shows the required operating temperature for each of the three transmission line conductors discussed above. The design limit for all three transmission line conductors is 75°C, meaning it is not acceptable for any of these conductors to operate continuously above this temperature.

HVDC Capacity		**Required Operating Temperature (°C)**		
MW	**Amps**	**2312 ACSR (~7 Spans of Conductor)**	**2607 ACSR (MO River Crossing)**	**2839 ACSR (Majority of HVDC Line)**
550	1100	Acceptable	Acceptable	Acceptable
900	1800	83 (Must Be Replaced)	73	74

Table 3: HVDC Transmission Line Conductor Ratings

At 900 MW, both the 2607 ACSR and the 2839 ACSR conductors would be within their design limit. The upgrades necessary to achieve the capacity increase on those segments of the HVDC transmission line are likely to consist primarily of replacing existing structures with taller structures to increase conductor-to-ground clearance at the higher operating temperature. The short segment of 2312 ACSR would be well beyond its 75°C design limit when operating at 900 MW. Therefore, the 7 spans of this conductor would need to be rebuilt with a larger conductor. This required modification to achieve 900 MW capacity on the HVDC transmission line is included in the cost estimate below.

3.3 Cost Assignment

The anticipated costs of upgrading the capacity of the existing HVDC line from 550 MW to 900 MW are shown in Table 4. Costs are presented in 2022 dollars, which were escalated from the original 2019 estimate to account for inflation. The 900 MW upgrade cost estimate is based on preliminary transmission structural engineering evaluations. If additional HVDC transmission line modifications or scope changes are found to be necessary during the development of the project, the costs presented in Table 4 may be impacted. To account for this possibility, contingency was included in the original estimates provided by transmission structural engineering.

HVDC 900 MW Upgrade *Project #A727 = 200 MW* *Project #A746 = 150 MW*	Estimated Total Transmission Line Upgrade Cost	Amount Assigned to Project #A727	Amount Assigned to Project #A746
HVDC T-Line 900 MW Upgrade	$ 58,000,000	$ 25,000,000	$ 33,000,000
HVDC T-Line AFUDC	(Included)	(Included)	(Included)
HVDC T-Line Contingency	(Included)	(Included)	(Included)
TOTAL - Transmission Line	**$ 58,000,000**	**$ 25,000,000**	**$ 33,000,000**

Table 4: HVDC Upgrade Project – Transmission Line Modifications Cost Breakdown

The cost of increasing the capacity of the transmission line from 550 MW to 900 MW will be assigned to the TSRs in its entirety. The TSR associated with Project A727 will be assigned the entire cost of increasing the capacity from 550 MW to 750 MW, consistent with the TSR amount requested for that project. The TSR associated with Project A746 will be assigned the entire cost of increasing the capacity from 750 MW to 900 MW, including the cost of the reconductored segment of 2312 ACSR discussed in Section 3.2.

Section 4: AC Interconnection Facilities

4.1 Background

The new VSC HVDC converter stations cannot be retrofitted into the existing converter station buildings, requiring that they be constructed on a new site nearby. Additional AC interconnection facilities must be constructed to re-connect the new converter stations to the existing transmission system near the existing points of interconnection. As noted in Section 2, the new HVDC converter stations will be designed to interconnect at 345 kV on the AC system side as part of preserving long-term capacity expansion opportunities to maximize use of the HVDC line.

To accommodate interconnection of the new HVDC converter stations, new AC interconnection facilities will be constructed including new 345/230 kV substations, 345 kV transmission lines, and 230 kV transmission lines. The AC interconnection facilities will be permitted and constructed by Minnesota Power as part of the HVDC Modernization Project.

4.2 Scope of Work

In Minnesota, to connect the new HVDC terminal to the existing AC system, the Project will require the construction of a new St. Louis County 345/230 kV Substation located less than one mile west of the Arrowhead Substation. The new HVDC converter station will be connected to the new St. Louis County Substation by a new 345 kV transmission line and the St. Louis County Substation will be connected to the existing Arrowhead Substation by two parallel 230 kV lines. At Arrowhead Substation, the two new 230 kV lines will be interconnected to the existing HVDC Pole 1 and Pole 2 bus positions, which will be rebuilt with higher-capacity bus and electrical equipment to accommodate the increased HVDC capacity. Additionally, a short portion of the existing ±250 kV HVDC Line in Minnesota will be reconfigured to terminate at the new HVDC converter station.

In North Dakota, a new Nelson Lake 230 kV Switching Station will be established to tie together the existing Minnesota Power Square Butte East – Bison 230 kV Line with the existing Great River Energy Square Butte – Stanton 230 kV Line. A second 230 kV circuit will be added between Nelson Lake and Square Butte East using existing double-circuit capable structures. The Project will then require an expansion of the Nelson Lake 230 kV Switching Station to add a 345/230 kV transformer and 345 kV line entrance. A new 345 kV line will be constructed from Nelson Lake to the new HVDC converter station, where a new 345 kV bus will be required to interconnect the new line. Additionally, a portion of the existing ±250 kV HVDC Line will need to be reconfigured to terminate at the new HVDC converter station.

Figure 2 shows the pre-project configuration of the existing Square Butte HVDC system and its interconnections to Square Butte East 230 kV and Arrowhead 230 kV. Figure 3 shows the post-project configuration after establishment of the Nelson Lake and St Louis County 345/230 kV Substations and interconnection of the new VSC HVDC converter stations.

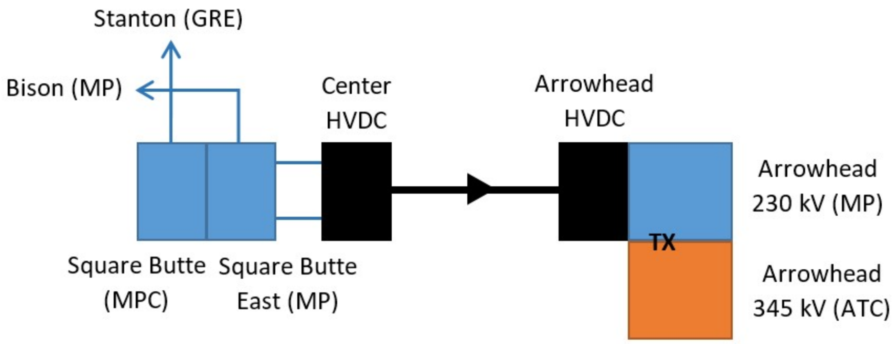

Figure 2: Pre-Project Configuration of HVDC Interconnections

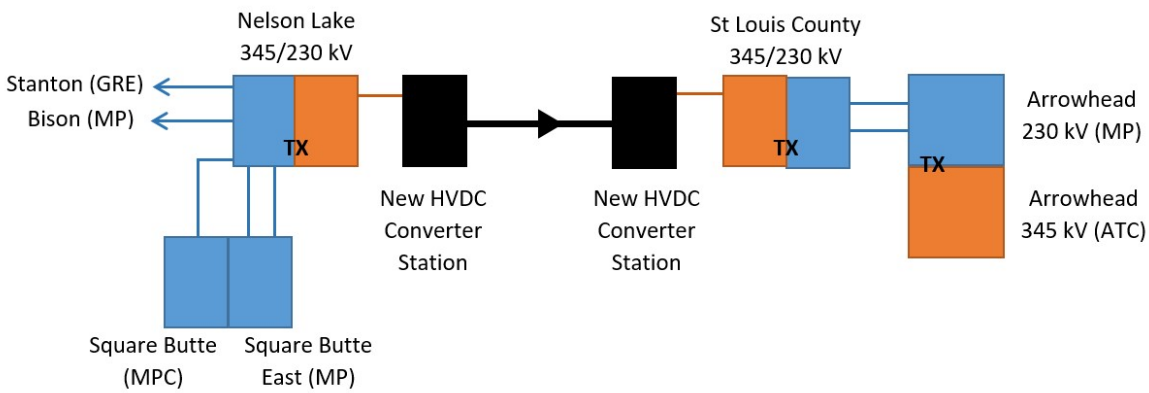

Figure 3: Post-Project Configuration of HVDC Interconnections

4.3 Cost Assignment

The anticipated costs of AC Interconnection Facilities necessary to connect the relocated VSC HVDC converter stations to the existing AC transmission system are shown in Table 5. Costs for AC interconnection facilities were developed based on the MISO MTEP22 Cost Estimation Guide and are presented in 2022 dollars. The MTEP22 cost estimation guide assumptions included adders for both AFUDC and contingency. If design assumptions change significantly during the development of the project, the base costs shown in Table 5 may change.

HVDC 900 MW Upgrade *Project #A727 = 200 MW* *Project #A746 = 150 MW*	**Estimated Total AC Interconnection Upgrade Cost**	**Amount Assigned to Project #A727**	**Amount Assigned to Project #A746**
Minnesota AC Interconnections	$ 55,000,000	$ 7,000,000	$ 5,000,000
North Dakota AC Interconnection	$ 40,000,000	$ 4,000,000	$ 3,000,000
Nelson Lake 230 kV Substation	$ 20,000,000	$ 4,000,000	$ 3,000,000
TOTAL - AC Interconnections	**$ 115,000,000**	**$ 15,000,000**	**$ 11,000,000**

Table 5: HVDC Upgrade Project – AC Interconnection Facilities Cost Breakdown

Due to Minnesota Power's previously-identified need to modernize the existing HVDC converter stations and the additional future capacity considerations included with the project, Minnesota Power is proposing to share in some of the AC Interconnection Facility costs. Therefore, as shown in in Table 5, the two TSRs will each be responsible for a portion of the AC Interconnection Facility costs and Minnesota Power will also bear a portion of the cost.

Section 5: Required Permits

Due to the relocation of the converter stations and the length of new AC interconnection facilities require to re-connect to the existing system, the HVDC Modernization Project will require state-level permits in both Minnesota and North Dakota. In Minnesota, a Certificate of Need and Route Permit will be required from the State of Minnesota. In North Dakota, a Certificate of Corridor Compatibility and a Route Permit will be required. Minnesota Power will obtain the necessary permits in both states.

Section 6: Project Schedule

The anticipated schedule for the Square Butte HVDC Upgrade is shown in Table 6. If there are delays in obtaining state-level permits, major changes in the expected scope of the HVDC Upgrade, or unanticipated delays due to supply chain or labor availability, then the schedule may change.

Milestone	Tentative Date	Months from Start
Facilities Construction Agreement Executed	May-2023	0
Minnesota Certificate of Need Application Filed	May-2023	0
North Dakota Certificate of Need Application Filed	Oct-2023	5
Begin Front End Engineering & Design with HVDC OEM	Jan-2024	8
Major Permits Received in Minnesota & North Dakota	Jul-2024	14
Order Long Leadtime Equipment for AC Substations	Nov-2024	18
Clearing Begins	Jan-2025	20
Construction of AC Interconnection Facilities Begins	May-2025	24
Construction of HVDC Transmission Line Upgrades Begins	Aug-2025	27
Receive Firm Proposal from HVDC OEM	Aug-2026	39
Execute Firm EPC Contract with HVDC OEM	Oct-2026	41
Construction of HVDC Converter Stations Begins	Oct-2027	53
Commercial Operation Date	Apr-2030	83

Table 6: Square Butte HVDC Upgrade – Anticipated Project Schedule

Bipole HVDC outages will be required throughout the construction period to facilitate the Transmission Line Modifications. To the extent reasonable, this transmission line construction will be coordinated with HVDC converter station outages during construction to minimize downtime as much as possible. Therefore, the transmission line modifications are expected to be executed in stages over the course of the HVDC Upgrade construction period.

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VSC HVDC Technology Attributes for the Future Power System

MISO Planning Advisory Committee Stakeholder Technology Workshop

May 31 – June 1, 2023

PRESENTATION OUTLINE

1. **Background – Minnesota Power's experience**
2. **Planning for a power grid with high amounts of variable generation**
3. **Technical attributes of Voltage Source Converter (VSC) HVDC**
   - A. **Long-distance transfer capability (covered by MISO 3/8/23)**
   - B. **Reactive power and voltage support**
   - C. **DC line fault clearing and recovery**
   - D. **Dispatch and controllability**
   - E. **Grid-forming & Black Start restoration**
4. **Conclusions**

Appendix

- A. **VSC-HVDC Projects Worldwide**
- B. **Comparison of 765kV AC and VSC-HVDC**
- C. **Conversion of AC Lines to HVDC Lines**

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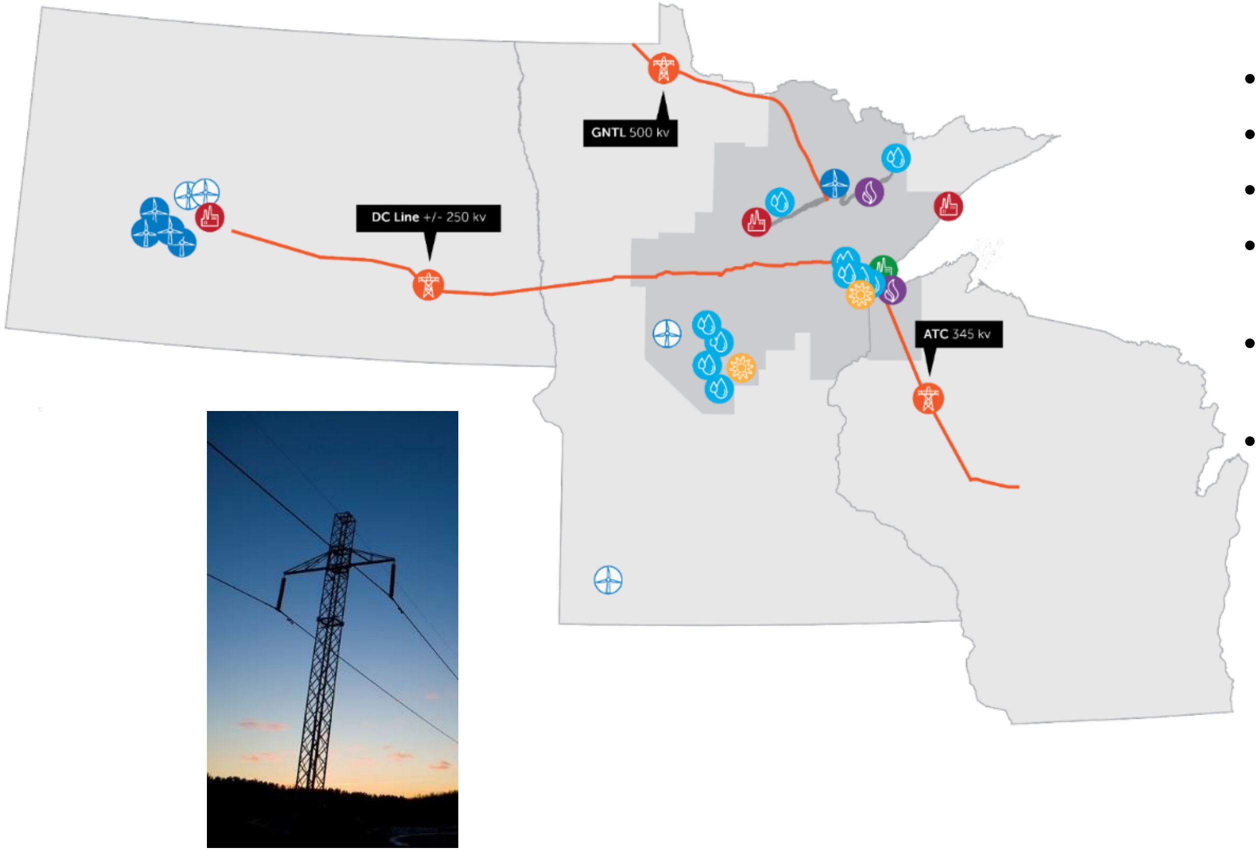
BACKGROUND: MINNESOTA POWER'S EXPERIENCE



The Square Butte HVDC Corridor

- 550 MW of existing capability (Center-Arrowhead)
- 465 miles of +/- 250 kV HVDC transmission line
- 3200 line structures and 2 converter stations
- Put in service in 1977 to deliver "coal by wire" from ND coal fields to MP customers in NE Minnesota
- Acquired by MP in 2009 and repurposed to deliver wind and renewable energy to MP customers
- Converter stations are now 45 years old and in need of modernization

When it was originally commissioned, Square Butte was the first long-distance project in North America to implement 12-pulse thyristor technology

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MP & RBJ HVDC TECHNOLOGY ASSESSMENT

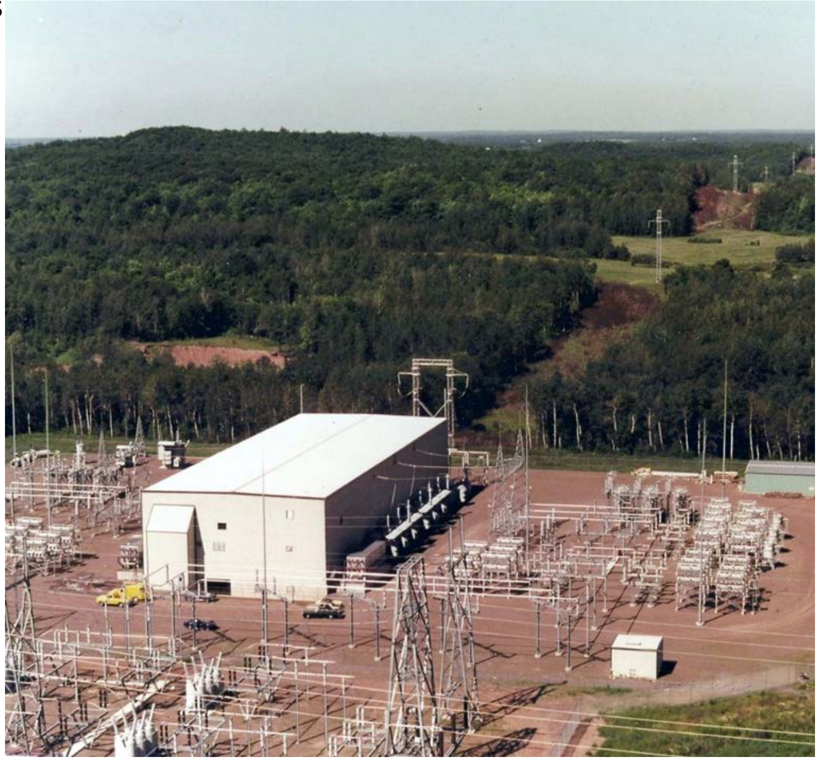
How to Develop a Long-Term Solution for Square Butte HVDC Modernization?
MP and RBJ Engineering worked together to complete a HVDC Technology Assessment and prepare recommendations on optimal near/term long-term solutions

__Key Considerations:__

1. **Modernization:** Address asset renewal needs by replacing existing converter stations ASAP
2. **Long-Term Technology:** Implement converter technology that does not become obsolete or un-upgradeable prior to normal end-of-life (35-40 years)
3. **Future Proof:** Robust to navigate changes in the surrounding transmission system, particularly for weaker transmission systems with high penetration of inverter-based resources
4. **Performance Features:** Self-sufficient in reactive power requirements, bi-directional dispatch capability, smooth & continuous P&Q control range, sub-hourly dispatchability without mechanical var switching, black start capable

Supplier Workshops: A questionnaire with 40 specific technical and commercial questions was developed and three major suppliers – Siemens, Hitachi, and GE – were invited to join MP & RBJ for individual one-day technical workshops to discuss the questionnaire and configurations. Suppliers were also asked to respond in writing to the questionnaire.

Existing Arrowhead HVDC Converter Station



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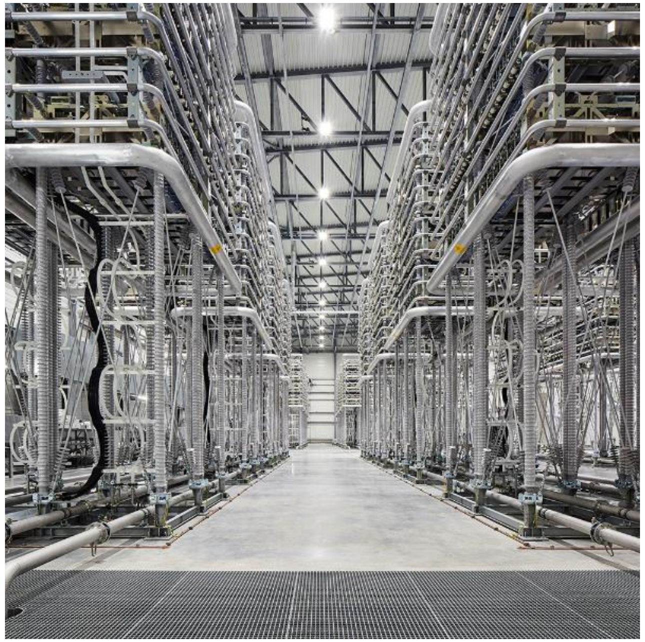
TECHNOLOGY ASSESSMENT FINDINGS

Conclusion: *VSC technology brings many technical advantages that LCC technology does not. As the power system continues to evolve around the clean energy transition, the value-added technical attributes of VSC technology will make it the most flexible and future-proof option for new HVDC development. VSC technology currently dominates the HVDC market, and some suppliers are moving away from LCC technology entirely.*

HVDC Technology Comparison	LCC	VSC
Future-Proof Technology	No	Yes
Reactive Power Requirements	AC Filters/Shunt Caps	Self-Provided
Dynamic Voltage Support	Not Included	Included
AC System Harmonic Impact	Requires AC filters	Minimal
Black Start Capability	No	Yes
Risk of Commutation Failure Due to AC faults	Susceptible	Relatively Immune
Minimum AC System Short Circuit Ratio < 2.0	No	Yes
Long-Term Outlook for Development & Support	Fewer Projects	More Projects
Outdoor Equipment	Most	Least
Building Size	Moderate	Larger
Converter Power Losses	Moderate	Slightly Higher
Bi-Directional Flow and Dispatch Frequency	Limited Flexibility	Highly Flexible
HVDC Line Fault Recovery Performance	Faster	Slower (Half-bridge)
Reliability & Availability	Similar	Similar
Expandability Options	Yes	Yes



VSC Converters. Photo Credit: Siemens Energy

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INITIAL POWER SYSTEM LANDSCAPE CONSIDERATIONS

Long-Term regional overlay solutions depend heavily on the nature of the grid in the future.

Decisions made today will define the transmission development path over the next several decades.

Critical Considerations:

- A highly variable, distributed, low baseload generation system is very different from what exists today
- *AC transmission solutions have large variability in reactive power over the load range and* depend more heavily on system strength and voltage regulation from traditional generation or other devices (e.g. synchronous condensers, STATCOMs, switched capacitors) requiring more technology additions
- *VSC HVDC transmission solutions* are less dependent on system strength and provide their own voltage regulation and controllability at the terminals with no requirement for reactive injection at intermediate points – which makes them better suited for a grid with large amounts of variable generation

System strength and voltage support, as well as additional grid-supporting attributes of VSC HVDC technology, tend to levelize the holistic cost comparison between VSC HVDC and AC-only solutions when considering the future, renewable-heavy power system.

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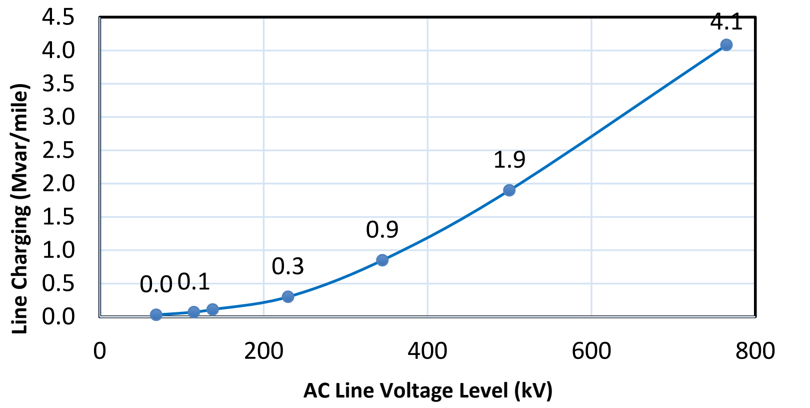
TECHNICAL ADVANTAGES OF VSC HVDC TECHNOLOGY

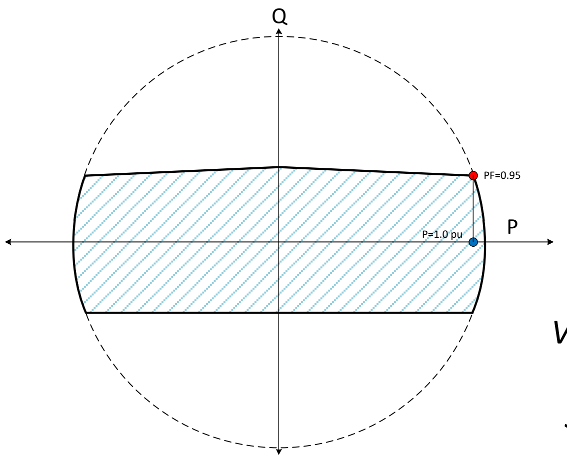
- The following slides provide a more detailed overview of some of the technical attributes of VSC HVDC, including:
  - Reactive support and voltage control
  - Internal fault clearing and power recovery
  - Power flow control and dispatchability
  - Grid-forming and Black Start restoration

REACTIVE SUPPORT AND VOLTAGE CONTROL

AC Transmission	VSC HVDC
AC lines generate large amounts of vars can affect by the broader AC system. They need to be absorbed at light load and sourced from the system at high load. This requires manual coordination of shunt reactors, series capacitors, STATCOMs and Tap-changing transformers	VSC HVDC terminals can be designed to produce or absorb reactive power to about 0.95 pf at maximum power transfer. HVDC can control both terminal AC voltages automatically to an operator setpoint.



765kV line ➔4Mvar/mile at nominal voltage



*For a 3000 MW bipole VSC HVDC line, this is like having **2x500 MVAR** STATCOMs on each end*

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IMPACT OF FAULT CLEARING & RECOVERY

- EHV AC and VSC HVDC line faults have different impacts on the surrounding AC power system
- For Bipole HVDC systems, Single pole faults retain inherent redundancy of transfer capability (50%) and voltage support from the healthy pole
- For Symmetrical monopole and Bipole systems, 100% loss of transfer needs to be planned for, but impacts can be managed in real time through HVDC system dispatchability if AC system has constraints
- VSC HVDC DC line fault clearing and recovery is different from EHV AC line fault clearing and recovery, but not necessarily worse
- Depending on EHV AC protection settings, recovery times may not be significantly faster than VSC HVDC, while VSC HVDC provides better support for surrounding system voltages during recovery

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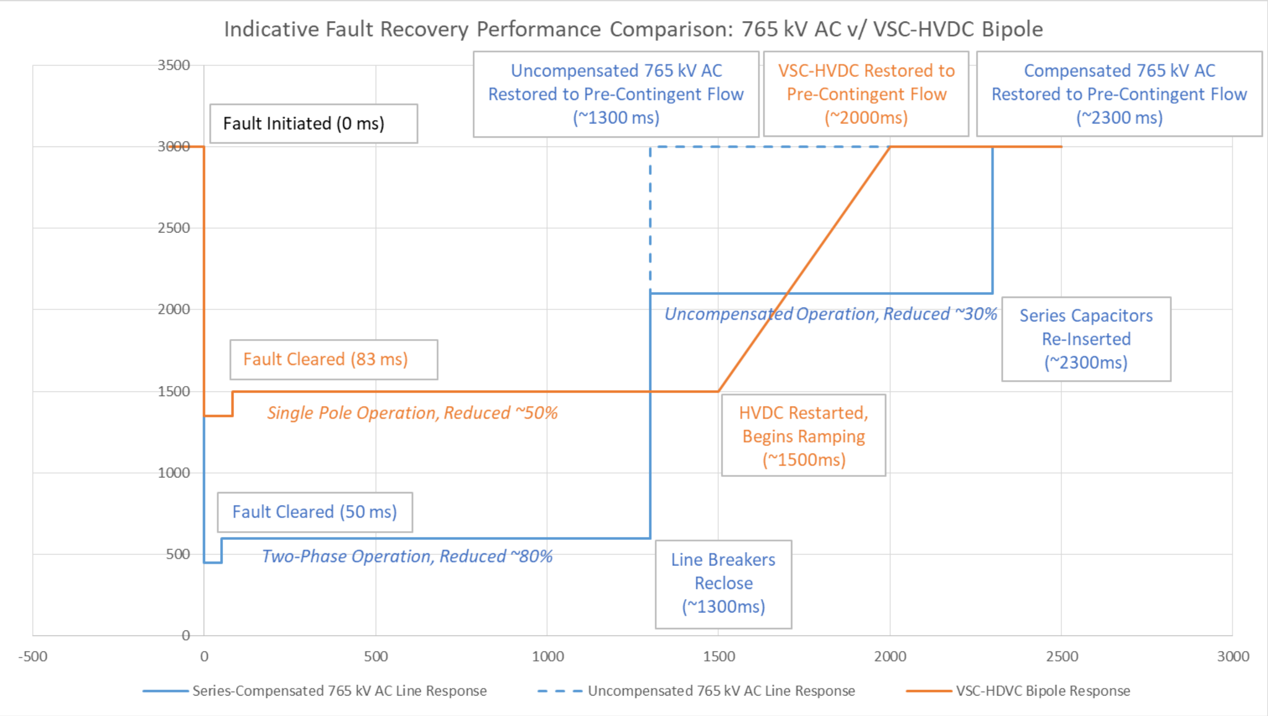
RECOVERY FROM LINE FAULTS - ILLUSTRATIVE EXAMPLE

Attribute	AC Line	VSC HVDC
Clearing Time	50 ms	83 ms
Power Transfer Reduction[1]	~80 percent	~ 50 percent
Reclose[2]/Restart	1300 ms	1500 ms
Return to Full Power[3] (Uncompensated)	~1300 ms	2000 ms
Return to Full Power (Compensated[4] AC Line)	2300 ms	N/A

Notes

1. Assuming single line to ground AC / single pole HVDC fault
2. Single pole trip and reclose time for 765 kV AC subject to detailed design studies to ensure full dissipation of induced currents. HVDC restart time based on half-bridge VSC converters.
3. Return to full power for 765 kV AC depends on surrounding system impacts. Generator tripping may reduce post-fault flow
4. For series-compensated AC transmission, series capacitor re-insertion is typically delayed from reclosing. Estimated about ~30% reduction in power transfer until series capacitors are restored to service



Conclusion: Fault clearing & recovery for VSC-HVDC is not significantly worse compared to EHV AC. In fact, some attributes of VSC-HVDC are better than EHV AC

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POWER FLOW CONTROL AND DISPATCHABILITY

- MISO has substantial experience in real-time optimization of regional interfaces including those with HVDC lines for thermal as well as transient or voltage stability limitations
  - Real-time fault recovery assessment being performed on interfaces using TSAT

    (examples include Square Butte, MN/WI, North Dakota Export, Coal Creek area, etc)
- VSC-HVDC provides full controllability of DC power transfer to optimize dispatch and manage underlying system impacts
  - Bidirectional flow from 0 to rated power in either direction
  - Redispatchable on sub-hourly time interval, including 5-minute dispatch capability
- Flexible & programmable control modes to respond to system conditions
  - HVDC lines may be set up to follow power angle difference between the terminals (similar to an AC line)
  - HVDC lines may be dispatched based on market price signals or the output of specific generators
- In case of Bipole outage, it is similar to the loss of a large AC transmission line, but inherent power flow controllability creates optionality to proactively manage underlying system impacts:
  - Real-time optimization based on contingency analysis can be used to set HVDC transfer limits
  - Offline studies may define HVDC transfer limits if AC outlets are not yet constructed
  - Nearby HVDC lines can be set to respond dynamically following bipole tripping

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GRID-FORMING AND BLACK START RESTORATION

- VSC converters allow the operation of portions of the power system asynchronously from the rest of the grid and include grid-forming controls that enhance reliable operations
- Grid-forming provides unique advantages and opportunities compared with AC transmission:
  - The VSC HVDC system can be used to operate large amounts of renewable energy resources or large load pockets with no direct AC interconnections. The converter acts as frequency and voltage control for the asynchronous system, enabling it to operate islanded from the rest of the grid
  - The VSC HVDC system can be used as a Black Start cranking path for power system restoration in either direction assuming at least one terminal has a strong source available. This capability is inherent in the converters but requires the installation of additional controls and a (very) modest amount of additional equipment such as diesel generation to supply startup aux power at the converter stations.
  - The VSC HVDC converters can be operated as STATCOMs when the HVDC line is unavailable, providing voltage control and reactive power support to the transmission system during normal operation or Black Start restoration
- Grid-forming controls mirror synchronous generator attributes like frequency response

SUMMARY OF KEY POINTS

- Voltage source converter (VSC) HVDC is the predominant technology in the HVDC market today
- Technical attributes of VSC HVDC make it uniquely suited for the clean energy transition, particularly:
  - Bulk transfer capability over long distances
  - Inherent dynamic reactive power and voltage control to support the grid
  - Dispatch and controllability for flexible power flow control & optimization
  - Grid-forming controls, including frequency & potentially synthetic inertia
  - Potential for black start restoration
- VSC HVDC converters on the receiving end can be like the dispatchable power plants of the future
- Ideal locations for VSC HVDC converters:
  - Retiring dispatchable generator locations, major load centers
  - Existing LCC HVDC converter stations, major transmission hubs
- Power flow control inherent in VSC HVDC technology can be leveraged to incrementalize HVDC solutions, allowing the underlying system & the regional grid to "grow into" high-capacity HVDC once it is established

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APPENDIX A
VSC-HVDC PROJECTS WORLDWIDE

VSC-HVDC PROJECTS WORLDWIDE

(NOT A COMPREHENSIVE LIST)

No	Project Name	Location	Length	Volt	Power	Year in Service
1	Cross Sound Cable	USA	40	±150	330	2002
2	Estlink	Estonia/Finland	105	±150	350	2006
3	Caprivi Link	Namibia	950	±350	300	2010
4	Trans Bay Cable	USA	85	±200	400	2010
5	BorWin1	Germany	200	±150	400	2012
6	EirGrid East West Interconnector	Ireland/UK	260	±200	500	2013
7	BorWin2	Germany	200	±300	800	2015
8	DolWin1	Germany	165	±320	800	2015
9	HelWin1	Germany	130	±250	576	2015
10	HelWin2	Germany	130	±320	690	2015
11	INELFE	Spain/France	64	±320	2x1000	2015
12	NordBalt	Sweden/Lithuania	450	±300	700	2015
13	Skagerrak 4	Norway/Denmark	244	±500	700	2015
14	SylWin1	Germany	205	±320	864	2015
15	DolWin2	Germany	135	±320	900	2016
16	Maritime Link	Canada	360	±200	500	2017
17	DolWin3	Germany	160	±320	900	2018
18	Caithness Moray	UK	160	±320	1200	2018
19	Hokkaido-Honshu	Japan	122	±250	300	2019
20	BorWin3	Germany	200	±320	900	2019
21	COBRAcable	Denmark/Netherland	325	±320	700	2019
22	Nemo Link	UK/Belgium	140	±400	1000	2019
23	NordLink	Norway/Germany	623	±525	1400	2020
24	ALEGrO	Germany/Belgium	100	±320	1000	2020
25	IFA2	UK/France	240	±320	1000	2020
26	North Sea Link	Norway/UK	720	±515	1400	2021
27	Pugalur-Thrissur	India	175	±320	2x1000	2021
28	SW Link	Sweden	250	±300	2x720	2021
29	ElecLink	UK/France	70	±320	1000	2022
30	Johan Sverdrup Phase 2	Norway	200	±80	200	2022
31	Savoie-Piedmont	Italy-France	190	±320	2x600	2023
32	Viking Link	UK/Denmark	740	±525	1400	2023
33	DolWin6	Germany	90	±320	900	2023
34	FAB Link	UK-France	2x180		1400	2023
35	Western-Isles	Scotland	156	±320	450	2023
36	Creyke Beck A	UK	130~	±320	1200	2023
37	Attica-Crete	Greece	335	±500	2x500	2023
38	Dogger Bank A Interconnector	UK	207	±320	1200	2024

No	Project Name	Location	Length	Volt	Power	Year in Service
39	Dogger Bank B Interconnector	UK	207	±320	1200	2024
40	DolWin5	Germany	130	±320	900	2024
41	Greenlink interconnector	Ireland/UK	190	±320	500	2024
42	QingchongHaifeng	China	100	500	2000	2024
43	Creyke Beck B	UK	130~	±320	1200	2024
44	Ultranet	Germany	340	±380	2000	2024
45	Baihetan-Jiangsu	China	2000~	±800	8000	2024
46	Northconnect	UK-Norway	655	±525	1400	2024
47	Norfolk Vanguard,wind farm	UK	110		1800	2025
48	Norfolk Boreas, wind farm	UK	110		1800	2025
49	Creyke Beck C	UK	203	±320	1200	2025
50	Sofia (Teeside B)	UK	227	±320	1400	2025
51	ZangdongnantoYuegangao	China	2500~	±800	10000	2025
52	Mares	UK-Ireland			750	2025
53	Biscay Gulf Link	France-Spain	370		2200	2025
54	A-Nord Gennany	Germany	300	525		2025
55	Gridlink	UK-France	160	l	1400	2025
56	Abud Dhabi	UAE	140	l	3200	2025
57	BorWin 5	Germany	230	±320	900	2025
58	Sunrise Wind	USA	160	320	924	2025
59	Champlain Hudson Power Express	USA	540	±400	1250	2025
60	SüdOstLink	Germany	500	525	2000	2026
61	Celtic Link	Ireland-France	750	320~ 500	700	2026
62	Sunzia	USA	550mi	525	3000	2026
63	SuedLink DC3	Germany	700	±525	2000	2027
64	SuedLink DC4	Germany	550	±525	2000	2027
65	Higashi-Shi1nizu	Japan	B2B		600	2027
66	Xlinks1	Morocco-UK	3800		1800	2027
67	AAPL	Australia-	3750		3000	2027
68	EasternLink (E2DC)	UK	196	525	2000	2027
69	Borwin 6	Germany	235	±320	980	2027
70	PGCILPang - Kaithal	India			2x2500	2027
71	Marinus Link (Phase 1)	Australia			750	2028
72	Neuconnect	Germany-UK	725	500	1400	2028
73	Nautilus	UK			1400	2028
74	DolWin4	Germany			900	2028
75	Beacon Wind 1	USA			1230	2028

No	Project Name	Location	Length	Volt	Power	Year in Service
76	Lake Erie	USA	117		1000	2028
77	Spain-France interconnector	Spain and France	500		2x1000	2028
78	Borwin4	Germany		320	900	2029
79	Xlinks2	Morocco-UK	3800		1800	2029
80	EastenLink (E4D3)	UK	490	525	2000	2029
81	BalWin1	Germany		525	2000	2029
82	Marinus Link (Phase 2)	Australia			750	2030
83	BalWin2	Germany		525	2000	2030
84	BalWin3	Germany		525	2000	2030
85	Eygpt-Saudi Arabia	Eygpt-Saudi			3000	2030
86	Eurolink	UK			1400	2030
87	Icelink	UK	1000		1000	2030
88	East Anglia 3	UK			1400	2030
89	Scotland to England HVDC	Scotland to England			2x2000	2030
90	Spittal to Peterhead HVDC	Scotland			2000	2030
91	Arnish to Beauly	Scotland			1800	2030
92	Grain Belt Express	USA	1280	600	4000	2030
93	TransWest	USA	732mi	500	3000	2030
94	UMEX	USA	465mi	525	1500/3000	2030
95	IJmuiden Ver Alpha	Netherland		525	2000	2031
96	IJmuiden Beta	Netherland		525	2000	2031
97	Jmuiden Ver Gamma	Netherland		525	2000	2031
98	Doordewind 1	Netherland		525	2000	2031
99	Doordewind 2	Netherland		525	2000	2031
100	Nederwiek 2	Netherland		525	2000	2031
101	Nederwiek 2	Netherland		525	2000	2031
102	Nederwiek 3	Netherland		525	2000	2031
103	BalWin2	Netherland		525	2000	2031
104	BalWin3	Netherland		525	2000	2031
105	BalWin4	Netherland		525	2000	2031
106	LanWin1	Germany		525	2000	2031
107	LanWin4	Germany		525	2000	2031
108	Australia-Tasmania interconnector	Australia	345	320	2x750	2028-2031
109	LanWin5	Germany	500~	525	2000	2035
110	Milan-Montalto	Italy	400	400	2000	2030/2032
111	Ionian-Tyrrhenian Backbone	Italy	800	500	2000/1000	2035
112	Adriatic Backbone	Italy	500	500	1000/2000	2032/2036

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APPENDIX B

COMPARISON OF 765KV AC AND VSC-HVDC

GENERAL ADVANTAGES OF VSC HVDC TECHNOLOGY

Broad HVDC advantages

- Can interconnect asynchronous AC systems without inadvertent power flow or transient stability concerns
- At a similar voltage level, a DC line can transmit more than double the power at around half the losses versus an AC line
- Narrower right-of-way footprint than for comparable capacity AC lines—one third to one half of the width for the same capacity
- Lower cost than AC for long-distance transmission—exact breakeven factor varies based on project details
- Low increase in short-circuit power (less impact on underlying system)
- Fast control of power flow and ability to schedule flows, and can be frequently re-dispatched
- Can operate as a generation follower in isolated systems
- Low outage rates and option for redundancy in case of faults
- Capacity is limited only by thermal limits, rather than an additional safe loading limit

Key attributes of VSC HVDC technology

- Independent and flexible active and reactive power control—improves power quality and avoids overloads on AC networks
- Optional Power oscillation damping—can help stabilize AC networks
- Black start capability: during AC network restoration VSC technology can provide system recovery ancillary service
- Firewall against cascading system disturbances
- Ideal support for AC grids with low short-circuit level and for the supply of fully passive systems
- Grid forming capability and compatibility with inverter-based resources

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COMPARING VSC HVDC TO 765 KV AC

CRITICAL ATTRIBUTES FOR SYSTEM INTEGRATION

Attribute	765 kV AC	VSC HVDC (±525 kV)
Power Transfer Capability	▪ Decreases substantially with line length/distance ▪ Enhanced with series/shunt reactive compensation	▪ Generally independent of line length/distance ▪ Main limitations associated with equipment ratings
Reactive Support and Voltage Control	▪ Generates large amount of reactive power at light load ▪ Consumes large amount of reactive power at high load ▪ Drastic swings require additional technologies & coordination (e.g. shunt reactors/capacitors, STATCOMs)	▪ Designed to produce or absorb reactive power at both converter stations ▪ Controls AC terminal voltages automatically for steady state and dynamic voltage regulation
Fault Performance: General AC System Faults External to the Transmission Line	▪ Generally do not trip for AC system faults but also do not provide significant additional support ▪ Low voltages may cause significant tripping of nearby renewable generation with long restart time	▪ Rides through AC system faults without blocking ▪ Designed to provide dynamic support during AC system faults, which can support improved system response ▪ Improved voltage response results in less tripping of nearby renewable generation
Fault Performance: Faults on the Transmission Line (765 kV or VSC HVDC)	▪ Fault impact will be seen broadly through the system ▪ Tripping results in significant rerouting of power onto the underlying system, increasing reactive requirements and potentially leading to overloading or voltage collapse ▪ Tripping the line results in loss of short circuit level in the area near the line, weakening the AC system	▪ Direct fault impact on AC system is minimized by HVDC connection configurations ▪ Vast majority of faults are single pole, meaning the remaining pole can continue to transfer real power and produce/absorb reactive power to support AC system ▪ Loss of VSC HVDC pole does not result in significant loss of system short circuit level

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AC VS DC SYSTEM INTEGRATION COMPLEXITY AND COST

AC Transmission	VSC HVDC

For fair comparison of HVDC link costs versus AC-only solutions, all costs associated with the AC solution system integration need to be considered:
▪ New interconnection facilities
  ▪ EHV and native voltage substations, buswork, circuit breakers, and instrument transformers
  ▪ New autotransformers to stepdown to native voltage
▪ Voltage and reactive power control
  ▪ Line shunt reactors, shunt capacitors
  ▪ Series compensation, (if applicable)
  ▪ STATCOMs or synchronous condensers
▪ Power flow control – *potentially*
  ▪ Phase shifters or other technology
▪ Underlying system impacts
  ▪ Short circuit level increases may require lower-kV circuit breakers to be replaced
  ▪ Underlying AC transmission line upgrades & expansion
 	
Final investment cost of AC-only solutions plus additional integration requirements becomes significant when all necessary support is considered.
	VSC HVDC is considered costly primarily due the high cost of HVDC converters, however there is significantly less additional system integration support required:
	▪ New interconnection facilities
	  ▪ AC (345kV) substations, buswork, circuit breakers, etc…
	▪ New HVDC converter stations on each end
	  ▪ Inherent voltage and reactive power control
	  ▪ Inherent power flow control
	  ▪ Other grid-supporting attributes…
	▪ Underlying system impacts
	  ▪ No impact on short circuit level
	  ▪ Impacts on underlying AC transmission system can be managed due to controllability and other features
	
	System integration of VSC HVDC is much less complex. It has inherent value-added attributes and can usually be integrated with fewer changes to the existing system.

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APPENDIX C
CONVERSION OF AC LINES TO HVDC LINES

FUTURE CONVERSION OF 765KV AC TO VSC HVDC

- Conversion of 765kV AC Line to HVDC is theoretically possible but:
  - It requires acquisition of more right of way (e.g. land owner impact) than ultimately will not be needed for the future HVDC line
  - It requires initial over-investment to include HVDC insulators on the AC line, as well as reactive support resources such as STATCOMs or synchronous condensers that are necessary to integrate 765kV transmission but not necessary for VSC HVDC
  - Where 765kV AC is not already present, it requires the development of design standards, spare equipment programs, and maintenance programs for 765kV equipment that is not intended to be a long-term solution
  - Upon conversion to HVDC, it may require the abandonment of 765kV equipment associated with the new line such as shunt reactors, circuit breakers, entire switchyards and large step up transformers (e.g. additional stranded investment)
  - It may negate or devalue investment in other 765kV AC lines if one line is converted for HVDC operation; or subsequent segmentation of the new 765kV line may inhibit future conversion to HVDC

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