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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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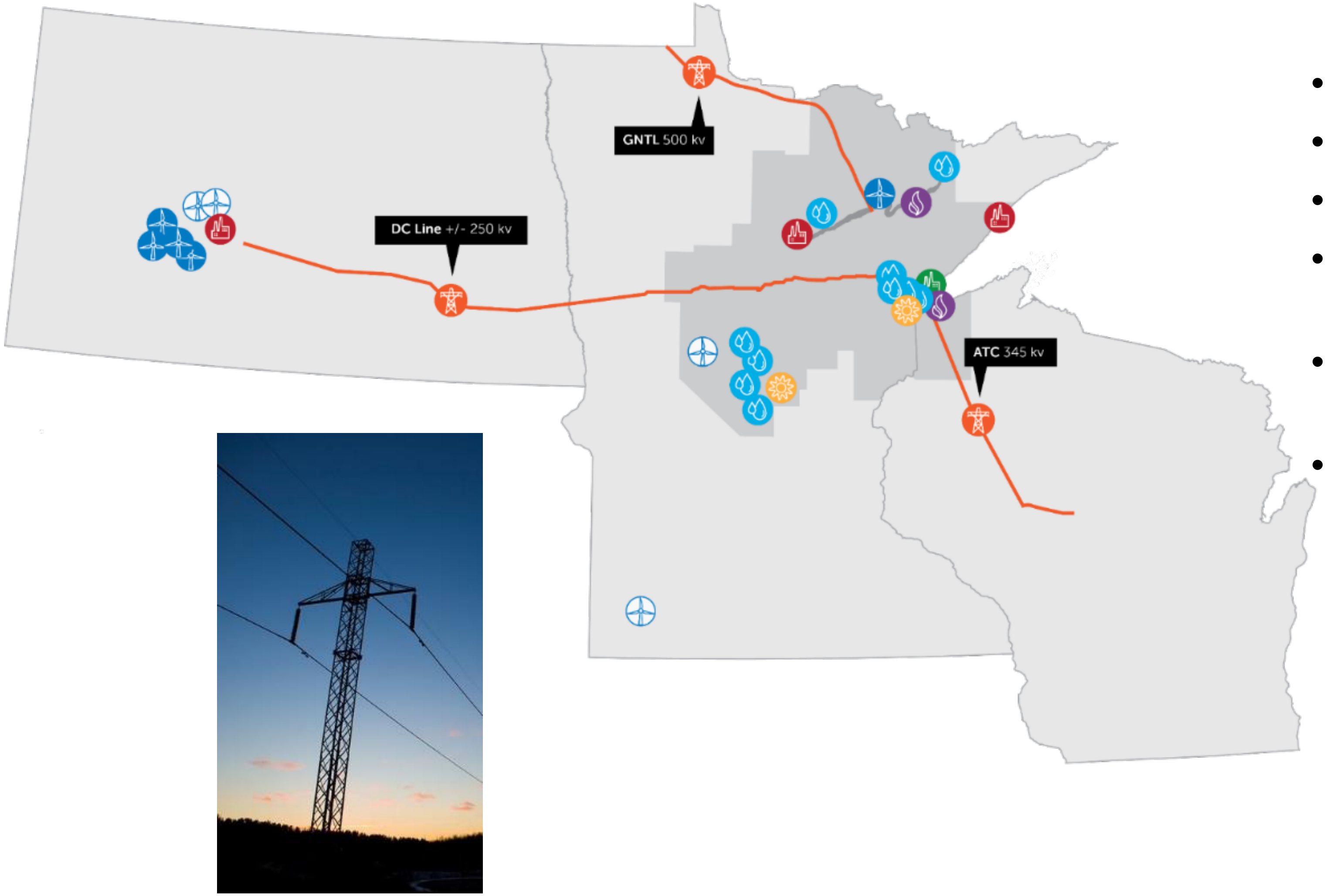
BACKGROUND: MINNESOTA POWER'S EXPERIENCE



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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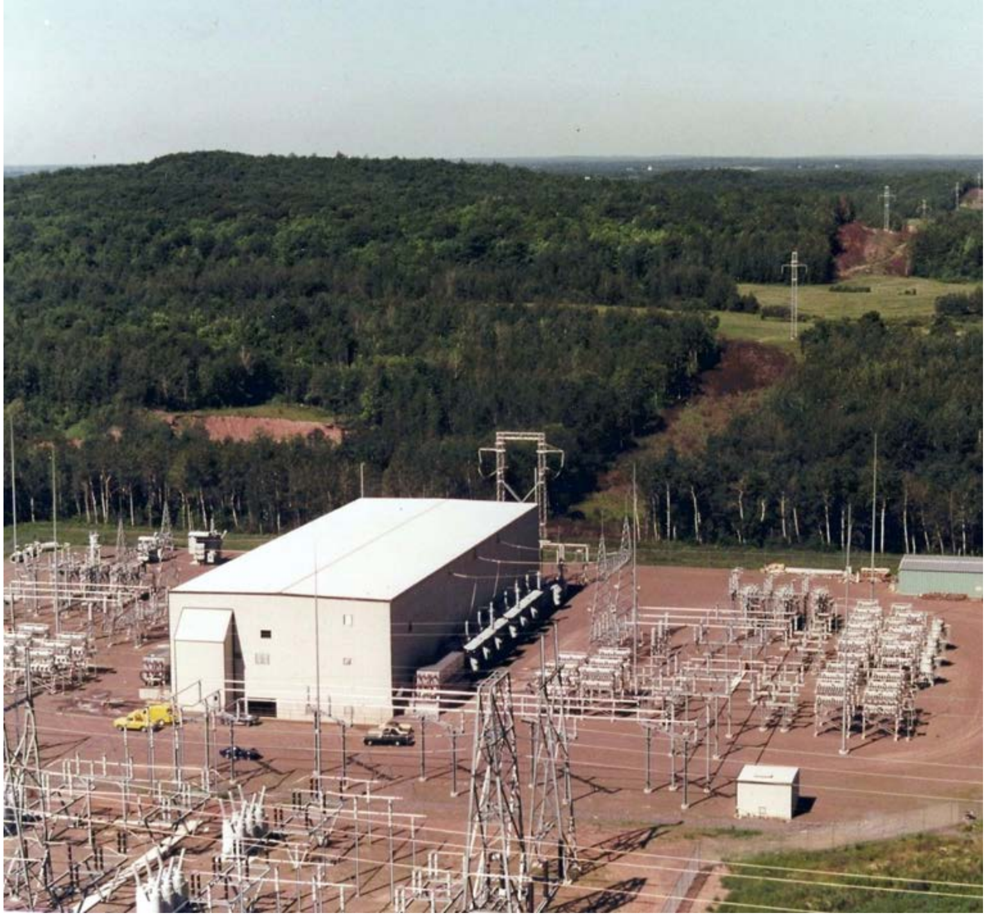
MP & RBJ HVDC TECHNOLOGY ASSESSMENT

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

Existing Arrowhead HVDC Converter Station



Key Considerations:

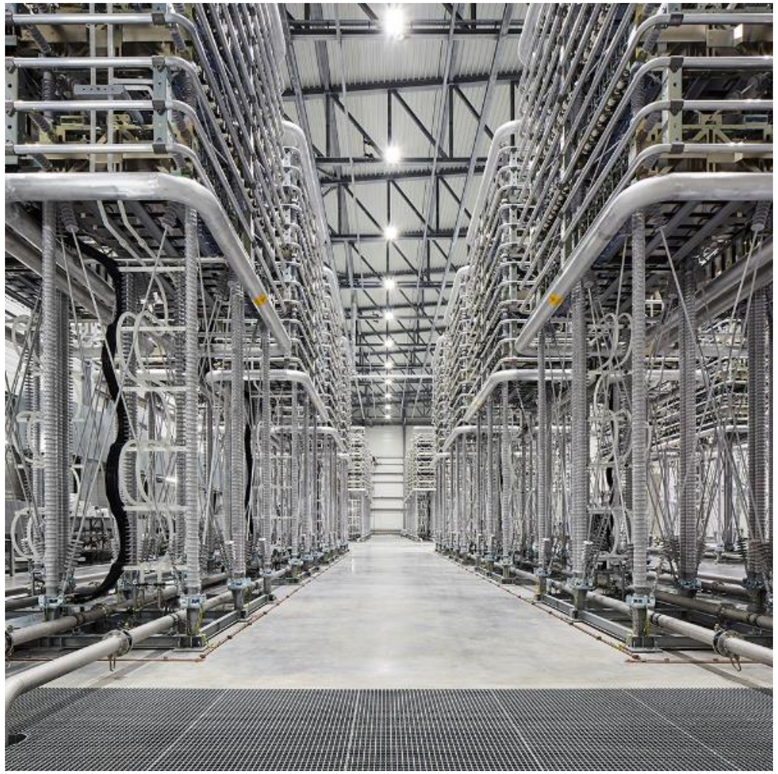
1. **Modernization:** Address asset renewal needs by replacing existing converter stations ASAP
2. **Long-Term Technology:** Implement converter technology that does not become obsolete or un-upgradeable prior to normal end-of-life (35-40 years)
3. **Future Proof:** Robust to navigate changes in the 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.

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

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.

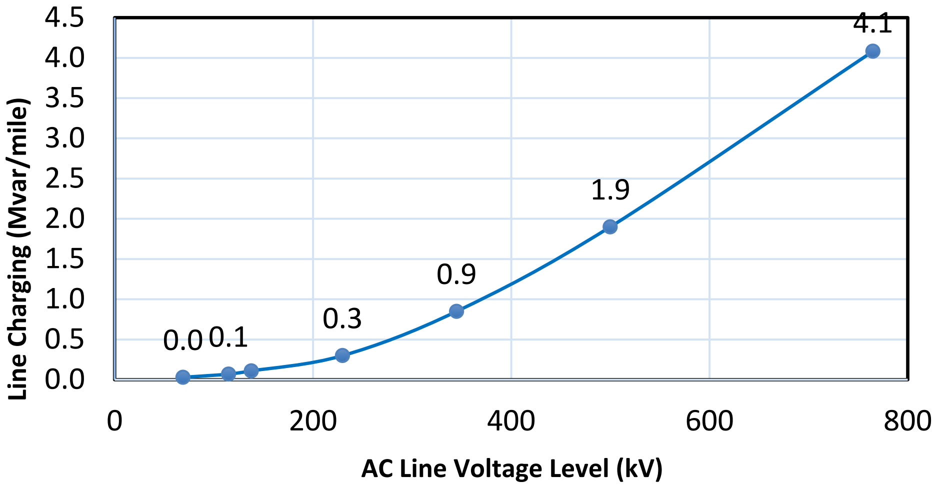
TECHNICAL ADVANTAGES OF VSC HVDC TECHNOLOGY

- 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

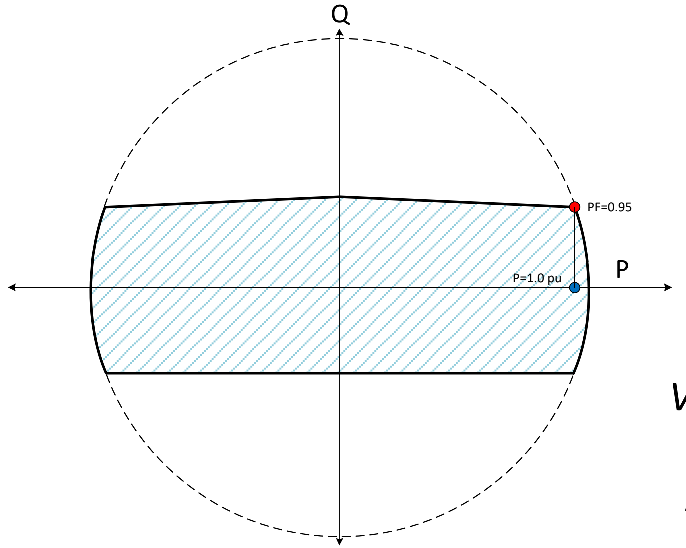
AC lines generate large amounts of vars can affect by the broader AC system. They need to be absorbed at light load and sourced from the system at high load. This requires manual coordination of shunt reactors, series capacitors, STATCOMs and Tap-changing transformers



765kV line ➔4Mvar/mile at nominal voltage

VSC HVDC

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.



*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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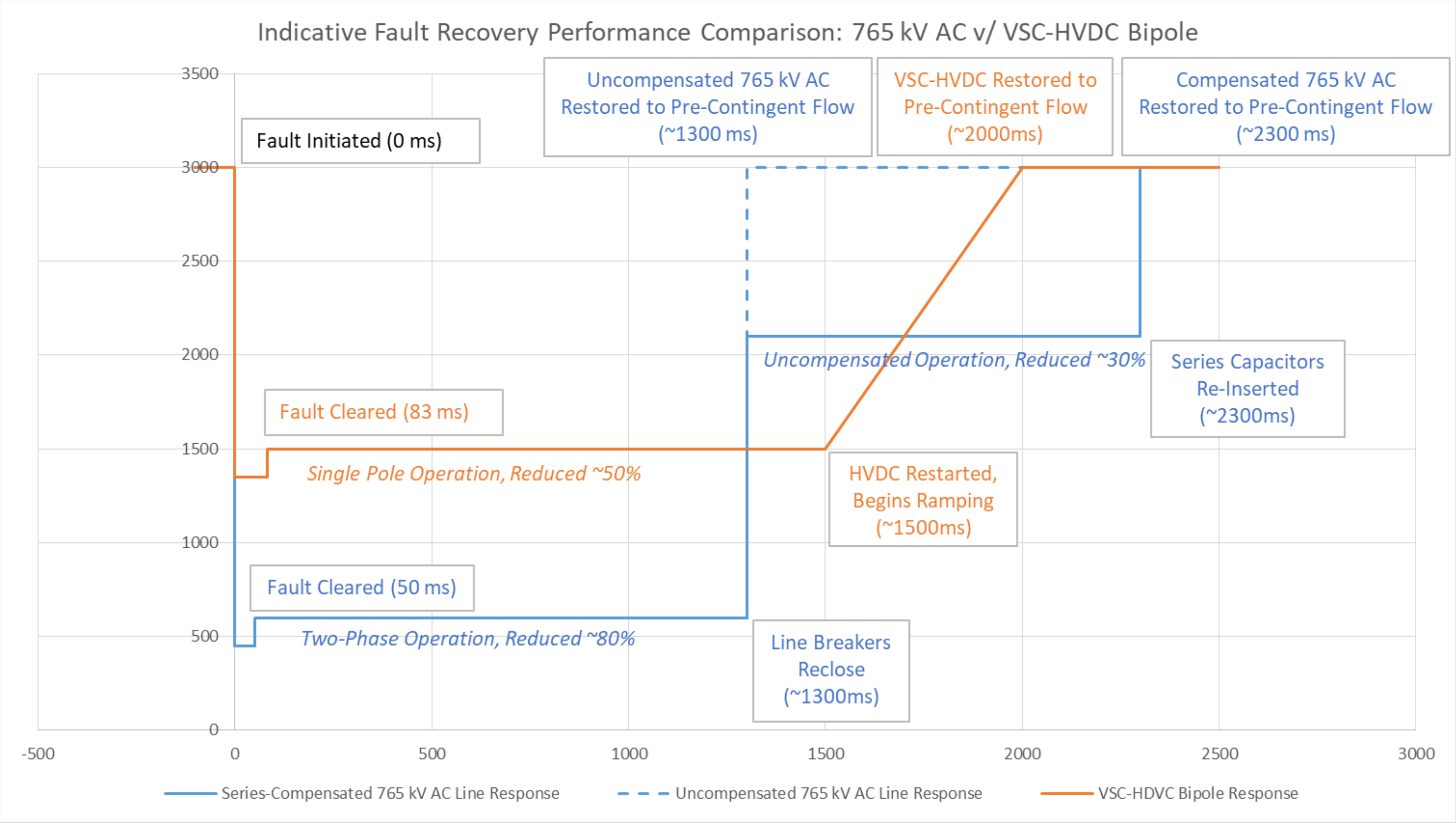
RECOVERY FROM LINE FAULTS - ILLUSTRATIVE EXAMPLE

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


Indicative Fault Recovery Performance Comparison: 765 kV AC v/ VSC-HVDC Bipole

Fault Initiated (0 ms)

Uncompensated 765 kV AC Restored to Pre-Contingent Flow (~1300 ms)

VSC-HVDC Restored to Pre-Contingent Flow (~2000ms)

Compensated 765 kV AC Restored to Pre-Contingent Flow (~2300 ms)

Uncompensated Operation, Reduced ~30%

Series Capacitors Re-Inserted (~2300ms)

Fault Cleared (83 ms)

Single Pole Operation, Reduced ~50%

HVDC Restarted, Begins Ramping (~1500ms)

Fault Cleared (50 ms)

Two-Phase Operation, Reduced ~80%

Line Breakers Reclose (~1300ms)

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

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
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	I	1400	2025
56	Abud Dhabi	UAE	140	I	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
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

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

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