Technology and Reliability Applications Overview

PJM HVDC Senior Task Force
Session 1

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SOO Green Project Overview

SOO Green HVDC Link

- Direct Connect Development Company is pioneering a new model to build High Voltage Direct Current (HVDC) transmission underground along existing rail rights of way, eliminating visual, environmental and land use impacts, and providing resiliency and system reliability benefits.
- The SOO Green HVDC Link, our flagship project, is a 350-mile, 2,100 MW, 525 kV underground HVDC transmission line from Iowa to Illinois, linking low-cost, utility-scale renewable generation in MISO with customers in PJM.
- SOO Green is the first major transmission project to cross the seam between MISO and PJM.

MISO Terminal (Killdeer Substation)	345 kV MISO Zone 3
PJM Terminal (Plano Substation)	765 kV PJM ComEd Zone
HVDC Converter Technology	Siemens 525kV VSC
Cable Technology	525 kV XLPE
Transmitted Power / Net of losses	2100 MW / 2035 MW
Route Distance	350 miles
Development Financial Close	Q4 2018
Initial Subscription	Q4 2020
Construction Financial Close	Q4 2021
Target NTP	Q1 2022
Target COD	Q4 2024

Click here to watch a two-minute video overview of the SOO Green HVDC Link project.

Motivations for the SOO Green Project

- Unlock high-quality energy resources needing a path to market
- Deliver large-scale, dispatchable renewable energy
- Demonstrate a lower-risk merchant transmission development model that:
    - Does not rely on eminent domain to secure right of way
    - Builds on the railroad co-location model successfully used for the national fiber optic network buildout
    - Reduces environmental impacts by installing HVDC cable underground

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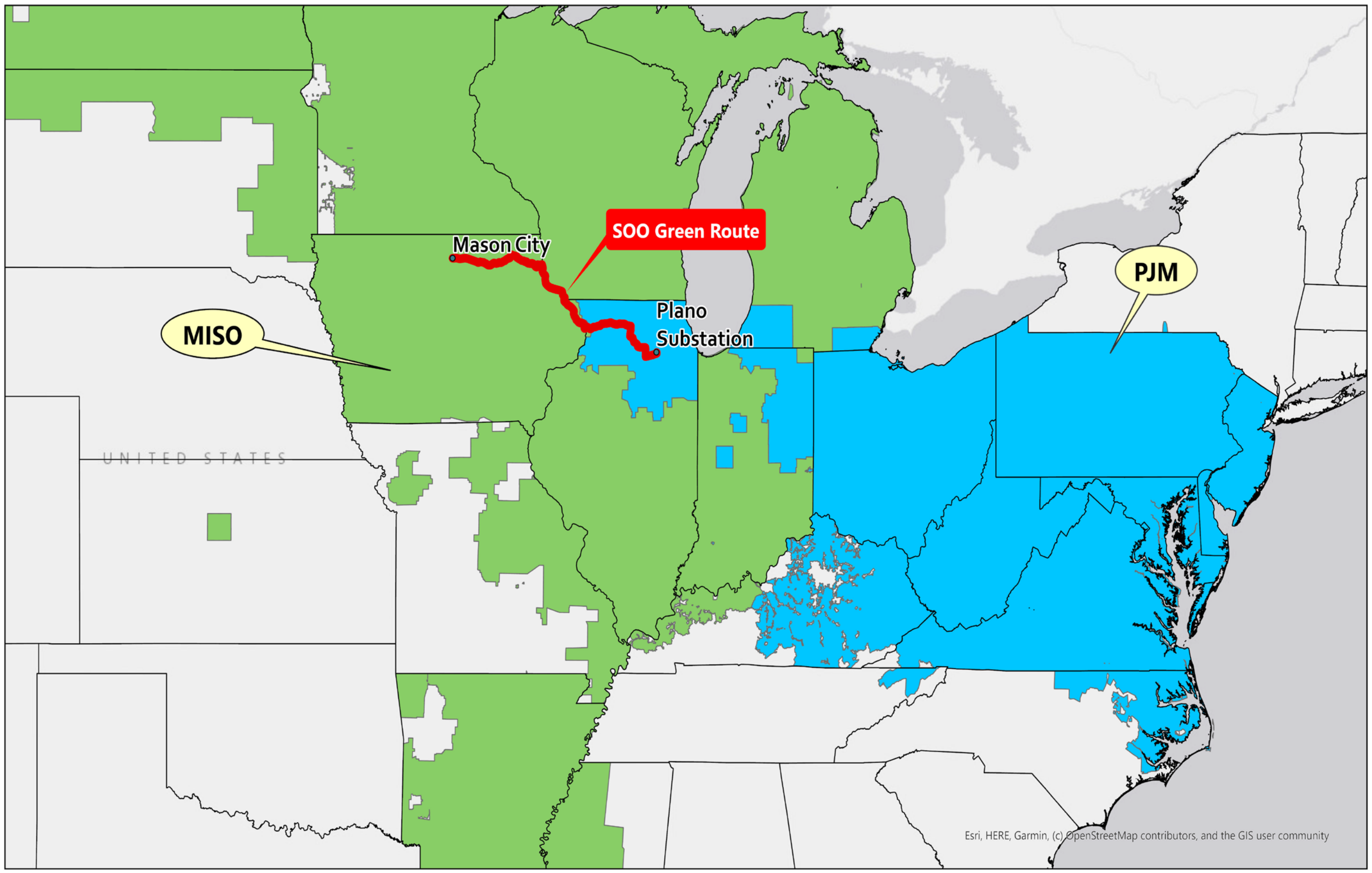
A New Model for Inter-Regional Transmission

- SOO Green will be the first major transmission project to connect the midwestern energy market (operated by MISO) to the eastern market (operated by PJM)
- A market-based solution, SOO Green will deliver low-cost, reliable energy from MISO to municipal, utility, and commercial customers in the PJM market
- Relieves congestion, connects sellers and buyers, and reduces market inefficiencies
- Enhances inter-regional reliability and resiliency



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HVDC Projects Follow the Pipeline Model

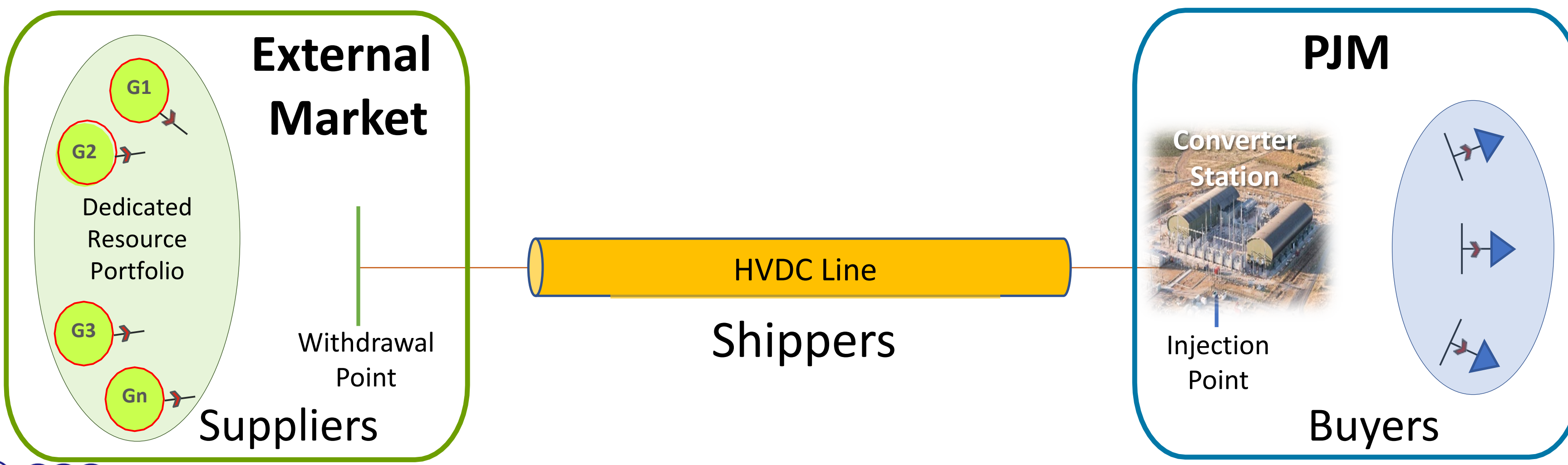
- HVDC projects source supply, provide transportation, and inject megawatts

Own, control or contract for output from generation resources

Purchase transmission capacity (may be paired with Suppliers/Buyers)

Contract with counterparties to purchase wholesale/retail products

- Merchant transmission operator (TOP) enters into long-term capacity contracts with Shippers who enter into long-term contracts with Suppliers for bundled energy and capacity
- TOP complies with NERC reliability requirements and follows RTO dispatch instructions
- Converter station as internal PJM capacity resource able to participate in the capacity market



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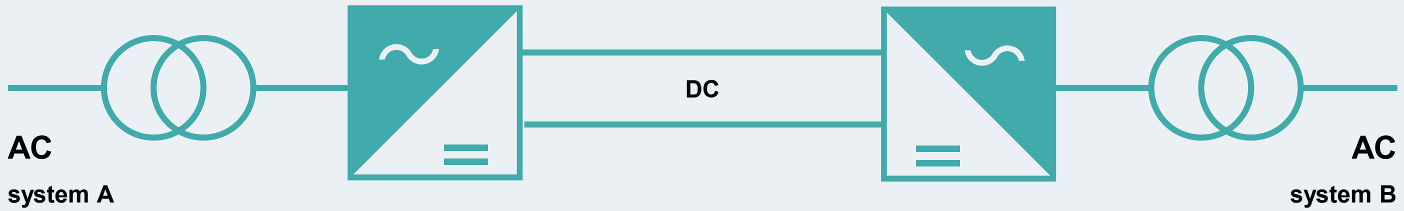
HVDC Converter Station Overview

Benefits and Advantages:
Technical Advantages of HVDC Controllability

SIEMENS
Ingenuity for life

HVDC is a unique solution for

- Long overhead lines with high transmission capacity and limited right-of-way
- Long cable transmissions
- Asynchronous interconnections
- New links in grids where short-circuit currents are at upper limits
- Fast control of power flow
- Precise control is ideal for merchant transmission systems



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Benefits and Advantages:
Technical Advantages of HVDC Controllability

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HVDC controllability is beneficial for

- Exact control of power flow in either direction
- Enhancement of AC system stability
- Reactive power control/support of AC voltage
- Frequency control
- Black start capability
- Emergency power functions
- Power oscillation damping

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LCC and VSC Technologies

HVDC Technology Characteristics: LCC and VSC

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Characteristics	Line-Commutated Converter (LCC) Technology (HVDC Classic)	Voltage-Sourced Converter (VSC) Technology (HVDC PLUS)
Rating	up to 10 GW	currently: 2 GW per bipole (FB) 1 GW per symm. monop. (HB)
Overload Capacity	Thyristor - very high	IGBT strictly limited
Total Losses (one station)	≤ 0,7 %	≤ 0.8 %
Voltage, POD & Frequency Control	Available	Available
Dynamic Performance	High	Very High
Filter Requirements	Typically. 50 % (in Mvar) of rated power transmission capability	None
Control of Reactive Power	Stepwise linear	continuously controllable (independent from active power)
Space Requirements	High	Less and flexible
Grid Access for weak AC Networks, lowest Short Circuit Ratio (SCR)	SCR typically > 2.5, lower SCR may require additional measures like installation of SCO or STATCOM, depending on system conditions	flexible, including supply of passive networks
Supply of passive Networks and Black-Start Capability	No	Yes, including System Recovery Ancillary Services
Suitability for Multi-terminal Schemes	possible depending on system conditions – typically limited to 3 terminals	Yes, no change of DC voltage polarity needed

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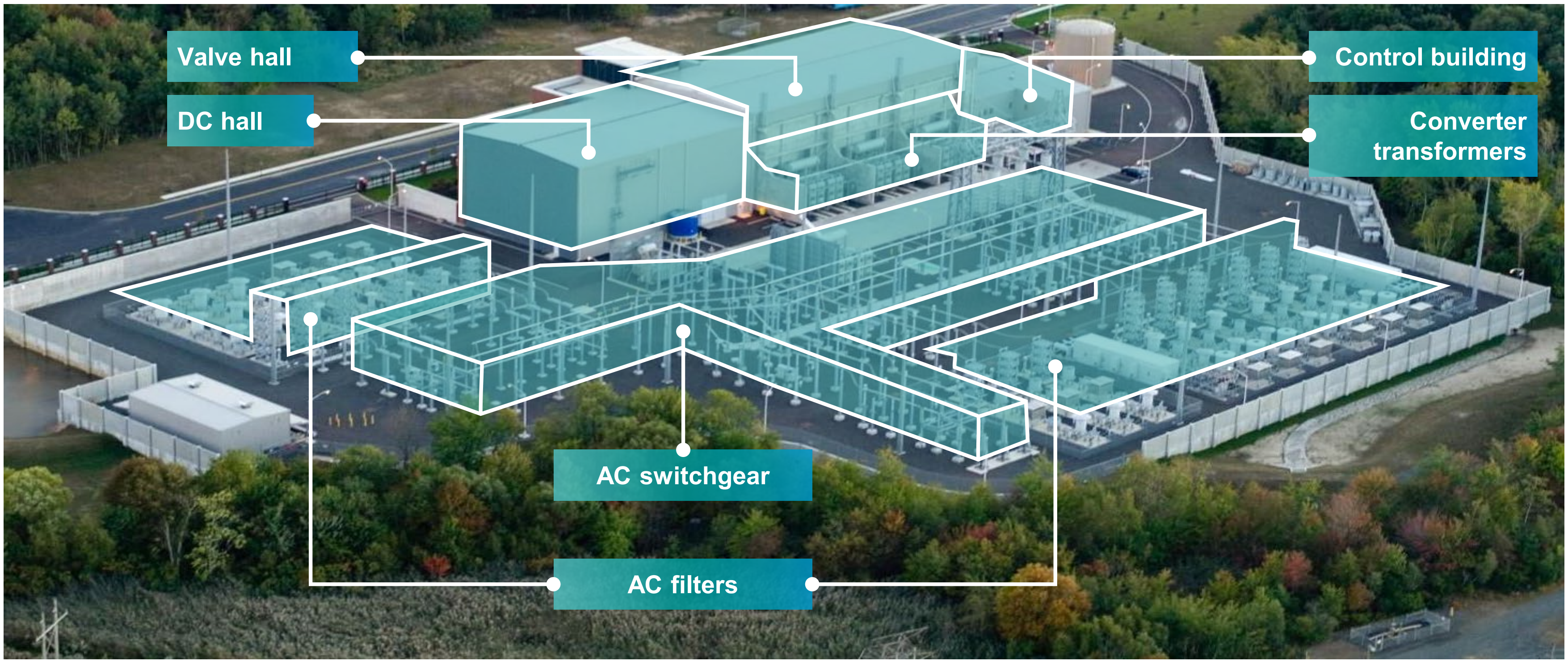
HVDC LCC Converter Station (HVDC Classic)
Station Design



HVDC VSC Converter Station (HVDC Plus)
Station Design

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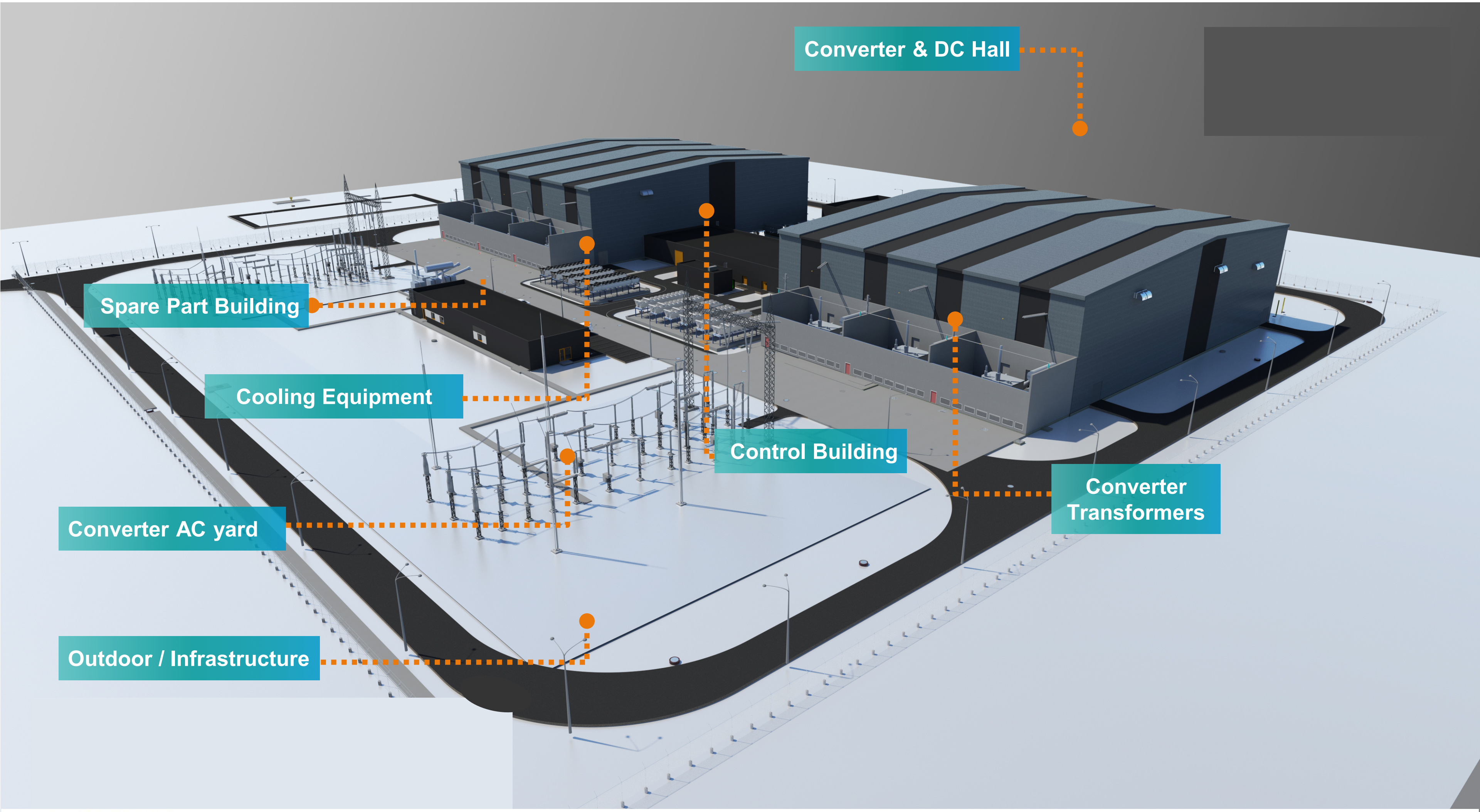

Technology and Operational Capability Discussion

Technology and Operational Capabilities

Attributes	HVDC Converter Station	CCGT Generator	Nuclear Generator	Energy Storage Resource
Fuel Source	Electric power from generating facility delivered by the power grid	Natural gas delivered using pipelines/ transportation	Uranium delivered using transportation	Electric power from generating facility delivered by the power grid
Categorization	Baseload, Intermediate load and Peaking scenarios	Baseload and Intermediate load scenarios	Baseload scenarios	Peaking load scenarios
Generator Real Power Control *				
Delivery of Energy at POI (for US grids)	Can deliver electric energy in the form of 3 phase, 60-Hertz alternating current at the nominal system voltage at the POI			
Governor/Speed Control	Can operate on electronic control to assist in maintaining interconnection frequency	Required to operate on unrestricted governor control to assist in maintaining interconnection frequency		Required to operate on electronic control to assist in maintaining interconnection frequency

* Attributes identified in PJM Manual 14D: Generator Operational Requirements

This table lays out technical and operational attributes of a typical PJM generator along with the functionality of an HVDC Converter Station

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Technology and Operational Capabilities

<table>
<tr><th>Attributes</th><th>HVDC Converter Station</th><th>CCGT Generator</th><th>Nuclear Generator</th><th>Energy Storage Resource</th></tr>
<tr><td colspan="5">Voltage and Reactive Control *</td></tr>
<tr><td>Voltage Regulation</td><td>Provide voltage regulation through automatic AC voltage control</td><td colspan="2">Require available field-excitation regulators</td><td>Require voltage regulators</td></tr>
<tr><td rowspan="2">Reactive Power Variation (under absence of automatic voltage regulator)</td><td colspan="4">Reactive output can be adjusted based on the grid system needs.</td></tr>
<tr><td>Reactive power can be adjusted independent of active power output</td><td colspan="3"></td></tr>
<tr><td>Start-Up Voltage Control Requirements</td><td>Operation of AC voltage control instantaneous on startup</td><td colspan="2">Operation of AVR in manual mode until full synchronism achieved</td><td>Operation of AVR in manual mode until full synchronism (through synchronous inverters) achieved</td></tr>
</table>

* Attributes identified in PJM Manual 14D: Generator Operational Requirements

This table lays out technical and operational attributes of a typical PJM generator along with the functionality of an HVDC Converter Station

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Technology and Operational Capabilities

Attributes	HVDC Converter Station	CCGT Generator	Nuclear Generator	Energy Storage Resource
Black Start Capability	Can be used as black start resources (VSC technology)	Open-cycle gas turbines can be used as black start resources	Not available	Can be used as black start resources
Typical Ramp-Up Time	Instantaneous	Typically between 10-30 minutes	Typically around 60 minutes	Instantaneous
Typical Ramp-Down Time	Instantaneous	Typically between 10-30 minutes	Typically around 60 minutes	Instantaneous

This table lays out technical and operational attributes of a typical PJM generator along with the functionality of an HVDC Converter Station

Interconnection and Reliability Application Discussion

Interconnection and Reliability Applications

Attributes	HVDC Converter Station	CCGT Generator	Nuclear Generator	Energy Storage Resource
Interconnection	Transmission level	Primarily Transmission level	Transmission level	Transmission, Sub-transmission and/or distribution level
Typical Reliability Applications				
1. Capabilities	Provides baseload, intermediate load and peaking load capabilities	Provides baseload and intermediate load capabilities	Provides baseload capabilities	Provides peaking load capabilities
2. Provides reactive support to local system	✓	✓	✓	✓
3. Provides reserves to the RTO	✓	✓		✓
4. Provides frequency control	✓	✓	✓	✓

This table lays out the interconnection and reliability applications of a typical PJM generator along with the functionality of an HVDC Converter Station

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Interconnection and Reliability Applications

Attributes	HVDC Converter Station	CCGT Generator	Nuclear Generator	Energy Storage Resource
Dispatchability	Fully dispatchable instantaneously with bi-directional continuous power transfer	Fully dispatchable with approx. 10-30 minutes of start-up time	Fully dispatchable with approx. 60 minutes of start-up time	Fully dispatchable instantaneously with bi-directional continuous power transfer (discharging vs charging)
Operational Availability	Operationally available based on contracted generation capacity	Operationally available based on contracted fuel supply		Operationally available for discharge based on existing charge and discharge efficiency
Congestion Management	Available for regional and local congestion management with potential reverse powerflow control	Available for local congestion management	Not widely used for congestion management	Available for local congestion management

This table lays out the interconnection and reliability applications of a typical PJM generator along with the functionality of an HVDC Converter Station

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