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Grain Belt Express: Steppingstone to Reginal Multi Terminal DC Grid

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Background

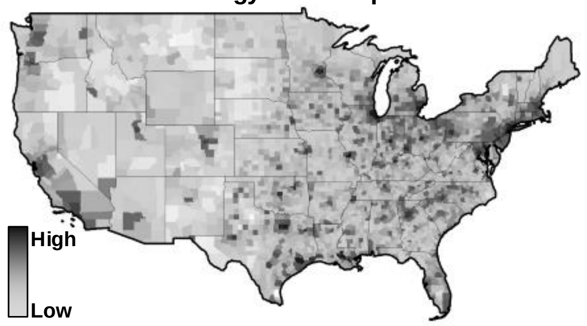
A North American Perspective of Electric Power Transmission

- United States consists of three interconnected asynchronous systems supplying energy to load within the lower 48 states
- Beginning of 2000, Regional Transmission Organizations were founded
  - To better manage grid reliability
  - Energy pricing through economic dispatch of generation in their energy markets
  - Allowing RTOs more flexibility in dispatching economic generation to meet load
- RTO footprints were generally established in areas of the system that already had import/export capabilities
- In areas where transmission capacity was limited, RTOs have undertaken transmission system expansions to improve the system efficiencies in their footprints

Generation Resources and Transmission Development

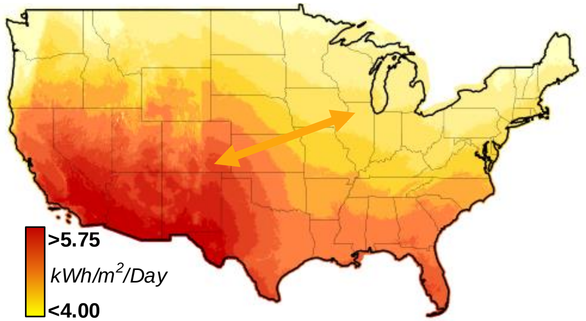
Legacy need-based development

Energy Consumption

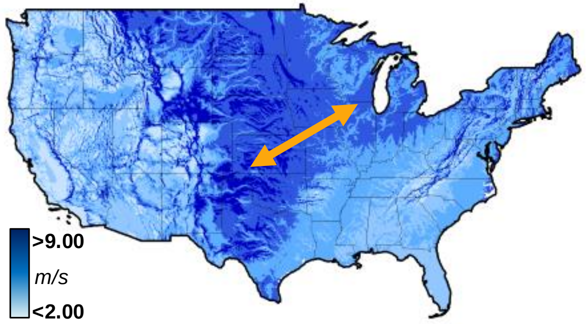


Existing Transmission Lines

Global Horizontal Solar Irradiance



Annual Average Wind Speed



Ref:
U.S. Census Bureau. US States [Data set]. MAF/TIGER Geographic Database. 2018
National Renewable Energy Laboratory. Net Electricity and Natural Gas Consumption. State and Local Planning for Energy. Accessed April 23, 2023
National Renewable Energy Laboratory. U.S. Annual Solar Global Horizontal Irradiance [Data set]. National Solar Radiation Database. February 22, 2018.

The load centers in the U.S. are in major metropolitan areas, most of which are along the coasts

As the electric systems developed, thermal generation (primarily coal-fired power plants) were built to support these load centers

Present high voltage transmission system of the United States, and its origins as a regional network of thermal generation and nearby load remain apparent

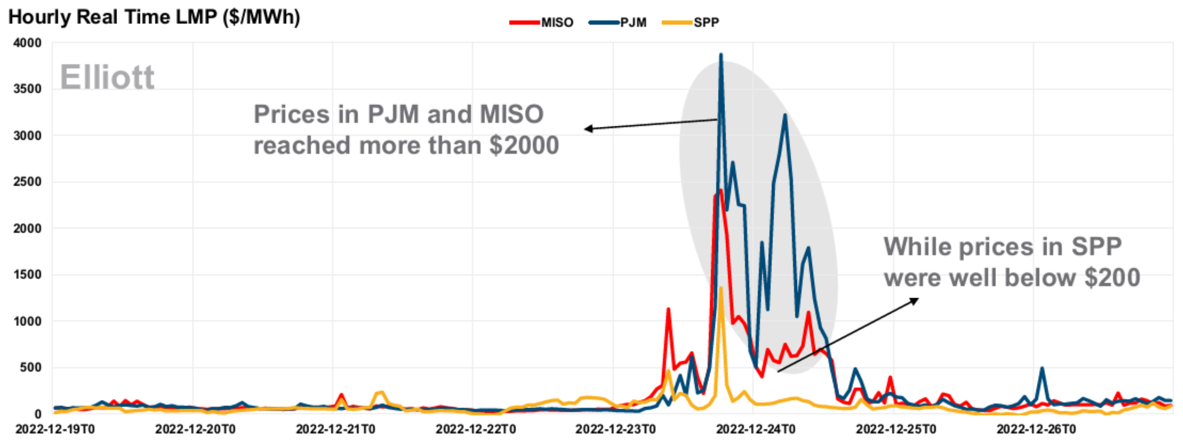
Most of the transmission lines are clustered around areas of high load, and there is limited transmission capacity extending across broader geographic regions

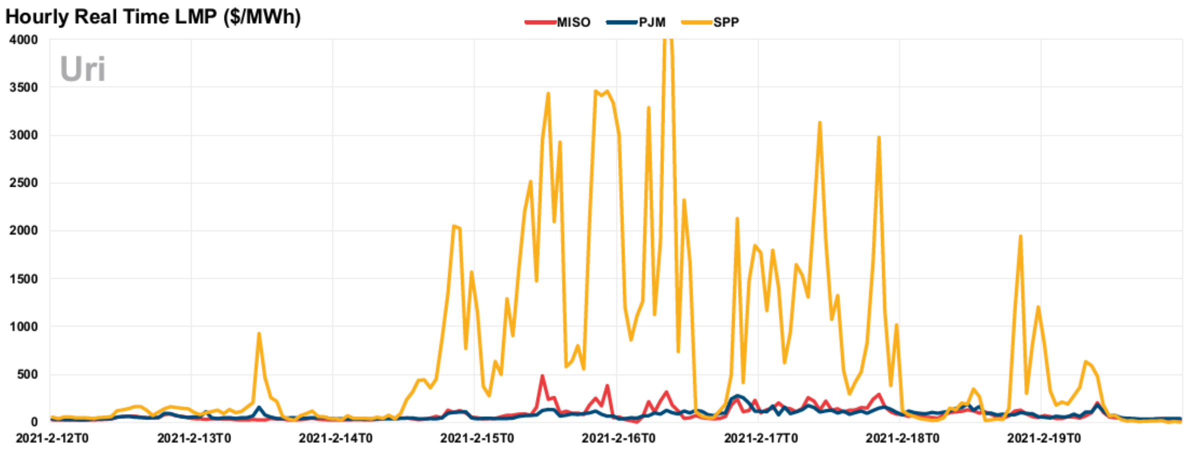
In the United States, substantial portions of the country's best renewable energy resources remain underutilized due to their remote location, local network congestion, and/or insufficient system strength

Energy Pricing Driven Motivation

Extreme Weather Events

Ref: Platts Market Data 3.0. Real-Time Locational Marginal Pricing [Data set]. S&P Global Market Intelligence. Accessed April 23, 2023





- The extent of the energy shortage in SPP with LMPs in excess of $1,000/MWh for 3 days and at one point exceeding $4,000/MWh
- During that time, PJM and MISO markets were not generally impacted by Uri, and the LMPs reflect that during that time period
- *“Grid Strategies LLC. “Transmission Makes the Power System More Resilient to Extreme Weather.” American Council on Renewable Energy. July 2021”* found that an increase in **1GW of transfer capacity between ERCOT and the southeast during Winter Storm Uri would have saved $1 billion**

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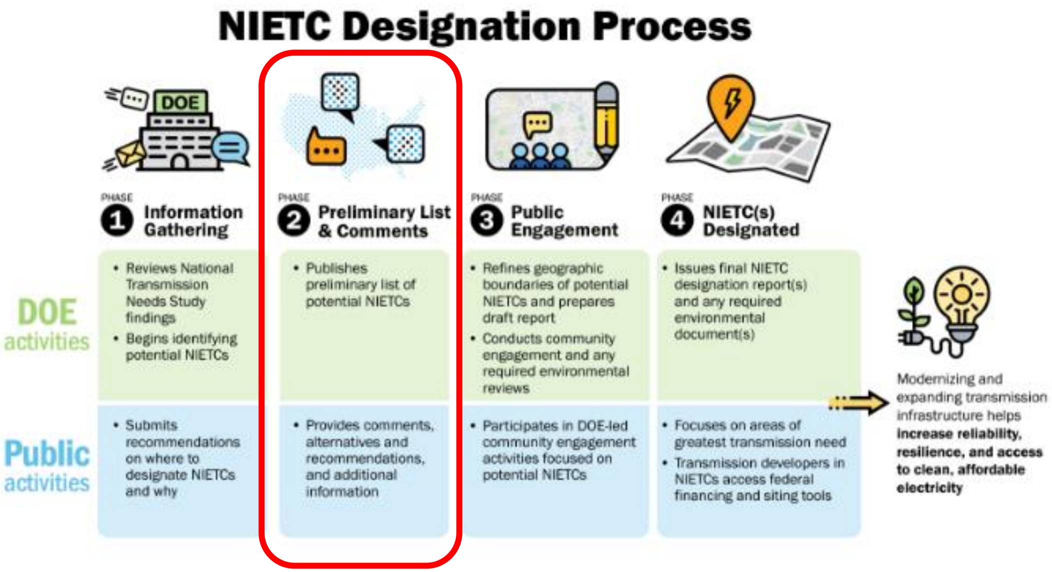
National Interest Electric Transmission Corridor Designation Process

https://www.energy.gov/gdo/national-interest-electric-transmission-corridor-designation-process

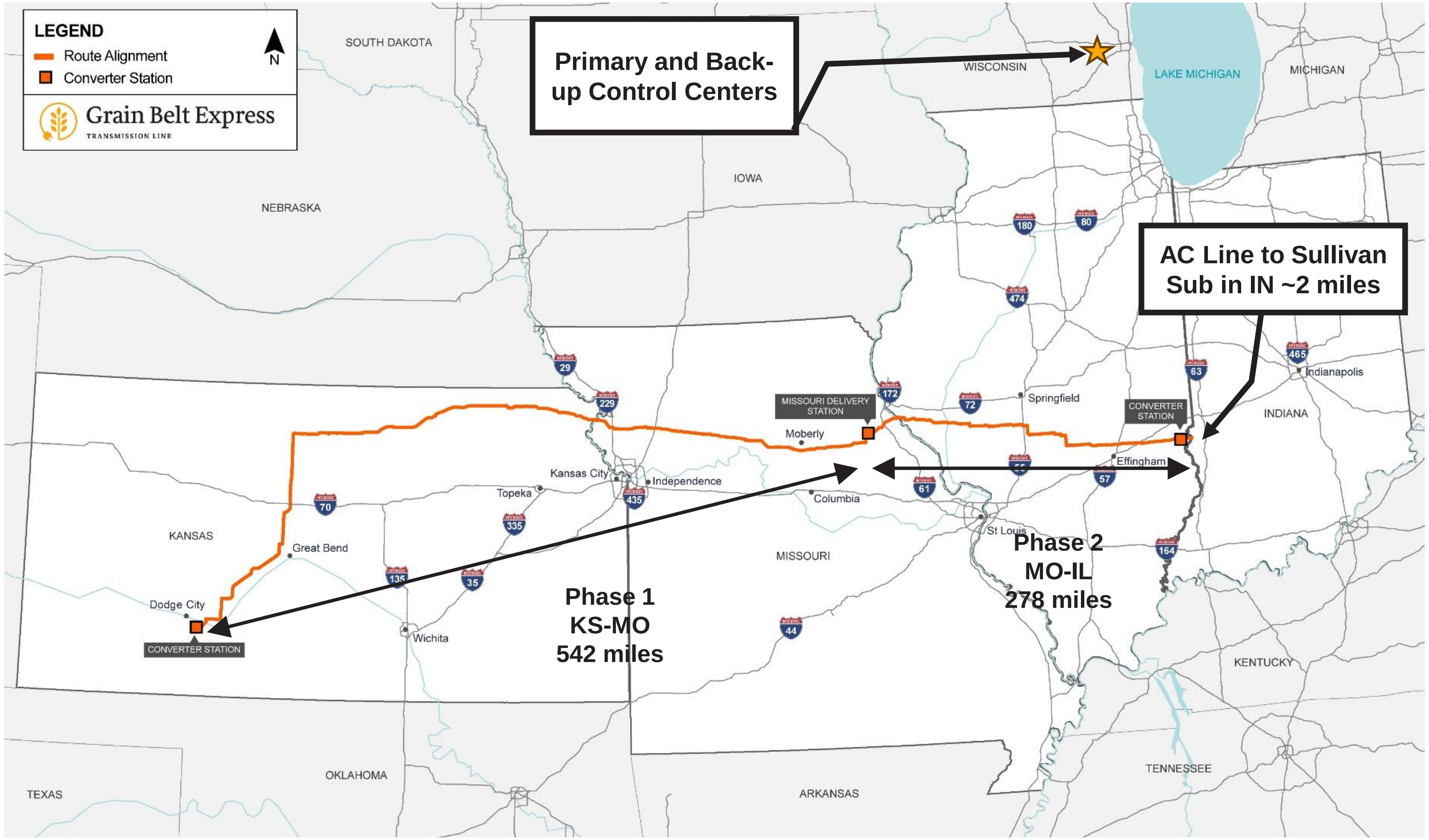
These corridors are designated based on areas where consumers are harmed by a lack of transmission in the area and that the development of new transmission would advance important national interests in that area, such as increased reliability and reduced consumer costs



Grain Belt Express HVDC

Fast Facts

- Approximately 5 miles wide, 780 miles long
- Includes portions of Illinois, Indiana, Kansas, and Missouri
- Includes parts of existing 345 kV transmission right-of-way
- Interregional corridor between PJM Interconnection, Midcontinent Independent System Operator (MISO), and Southwest Power Pool (SPP)



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Project Profile

Grain Belt Express
An Invenergy Project

PROJECT SPECIFIC: PHASE 1

- Approximately 542 miles
- ± 600kV High Voltage Direct Current (HVDC)
- Size 5,000 MW
- Bi-pole
- Bi-directional
- Phase 1 → 2,500 MW
- COD Phase 1 → 2028 - 2029
- Kansas - Interconnected with SPP/ITC Midwest
- Missouri – Interconnected with AECI and MISO/Ameren

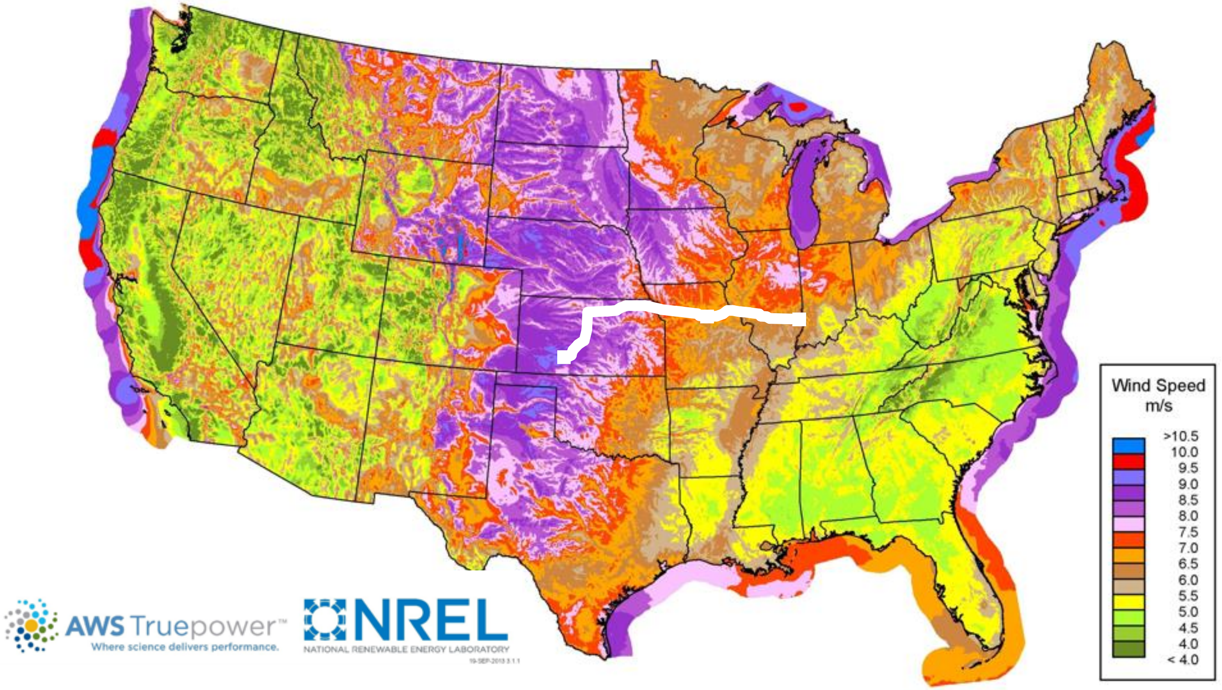
PROJECT SPECIFIC: PHASE 2

- Approximately 278 miles
- Phase 2 size → 2,500 MW
- COD Phase 2 → 2030 - 2031
- Indiana - Interconnected with PJM/AEP

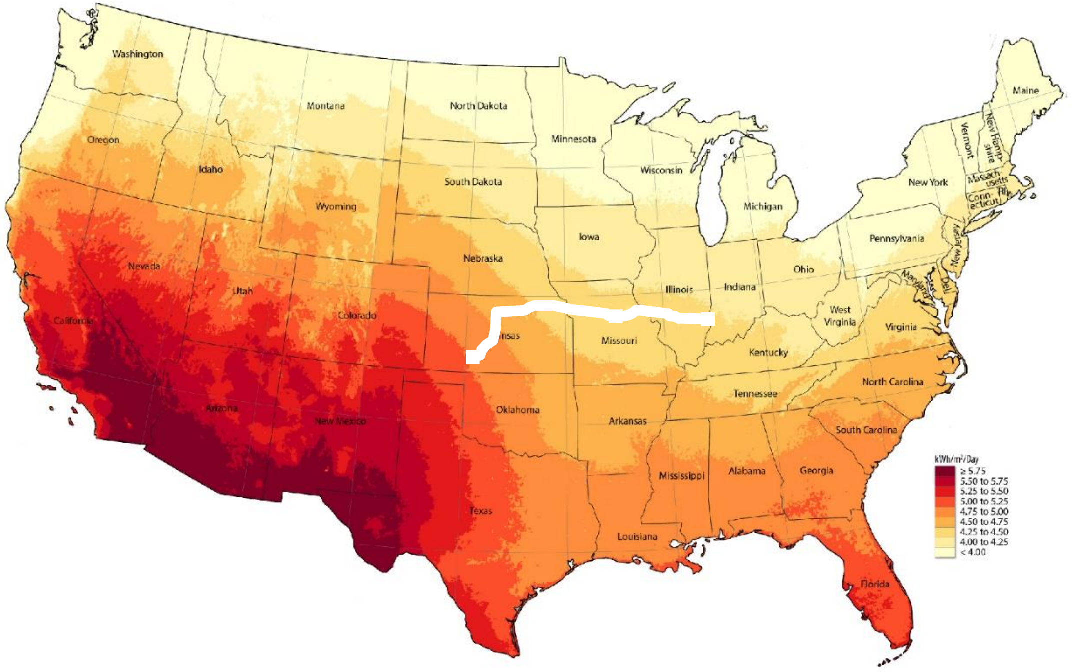
Committed to FERC and applicable state commissions to sign on to an RTO Open Access Transmission Tariff (OATT)

Grain Belt will unlock access to one of the strongest combined wind and solar energy resources in the United States.

United States - Land-Based and Offshore Annual Average Wind Speed at 100 m



Global Horizontal Solar Irradiance
National Solar Radiation Database Physical Solar Model



Grain Belt Express – Project Design

Key Design Parameters	
Nominal DC Voltage	±600 kV
Nominal AC Voltage	345 kV
Delivered Power	5,000 MW
Converter Topology	Bipole with DMR
Converter Type	VSC

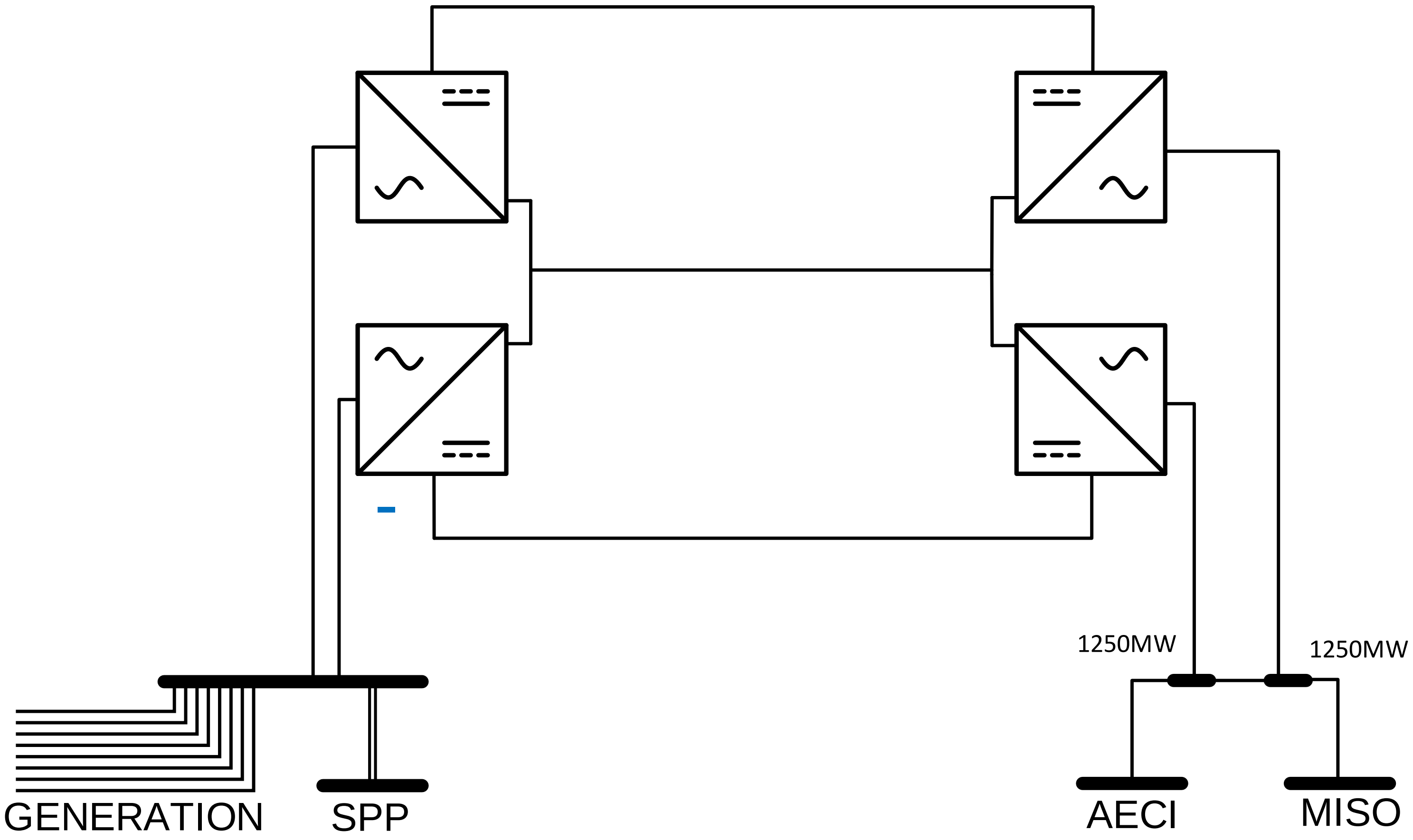
Key Advancements in Technology:

- Power and voltage ratings of VSC-HVDC
- Multiterminal HVDC grid control
- VSC-HVDC DC fault response
- Integration of renewables with VSC-HVDC

Grain Belt Project Technical Capabilities and Impact on Reliability as an Interregional Line

- The Grain Belt Project will have unique reliability benefits and efficiencies as an interregional merchant HVDC transmission project.
- HVDC projects can operate bidirectionally and act as generation at the delivery point, avoiding the same transmission losses, loop flows, and other issues associated with AC transmission.
- Grain Belt can have a significant diverse mix of renewable generation (solar, wind and battery) that can be directed to the region in greatest need.
- Whenever an emergency is declared by any of the three RTOs, Grain Belt and its partners can cause scheduled deliveries to be interrupted and re-routed meet the emergency need.
- The fact that Grain Belt and its interconnected renewable projects will be built on a merchant basis means that customers will not be allocated the bulk of the costs of Grain Belt and yet will be the beneficiaries of the reliability services that this project will deliver.

GBX Phase 1 Preliminary One Line Diagram



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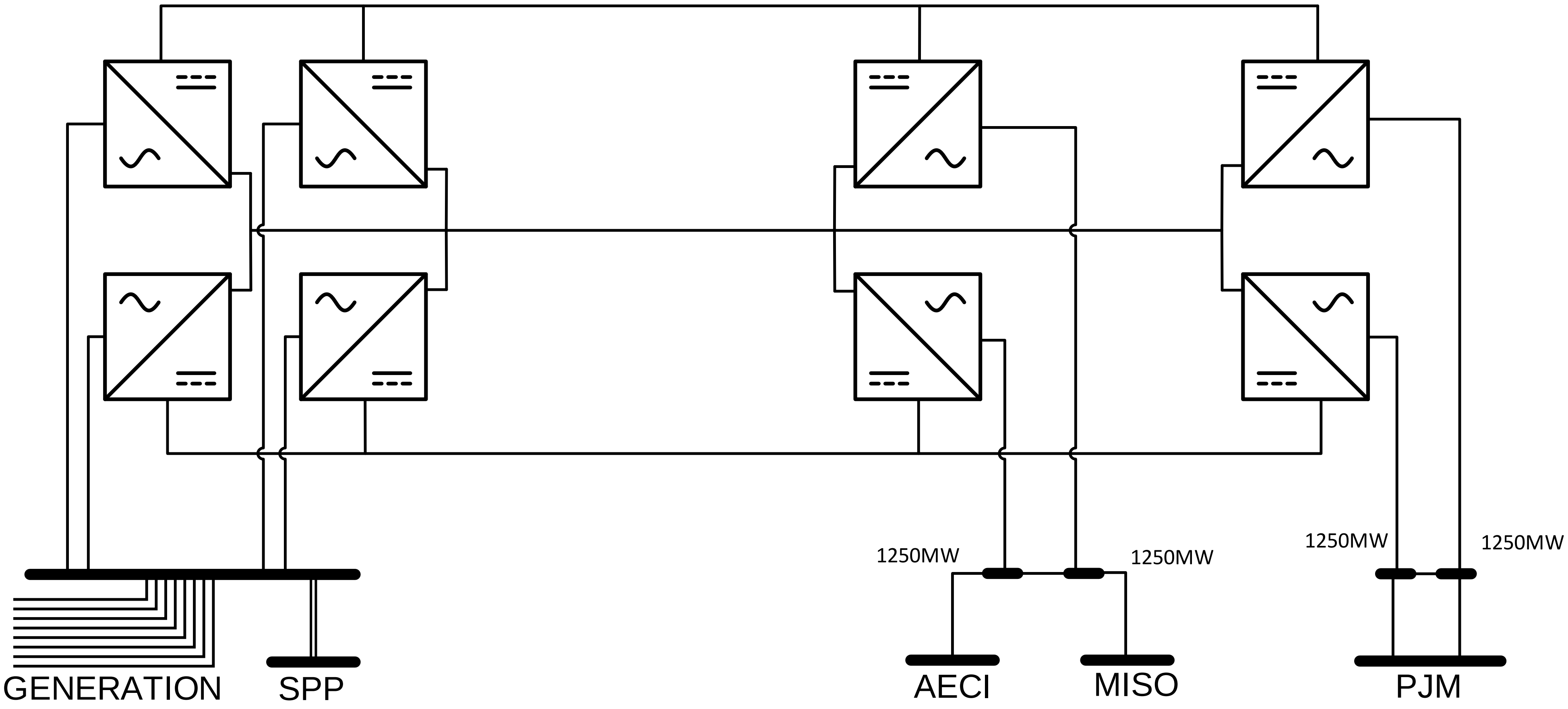
GBX Phase 2 Preliminary One Line Diagram



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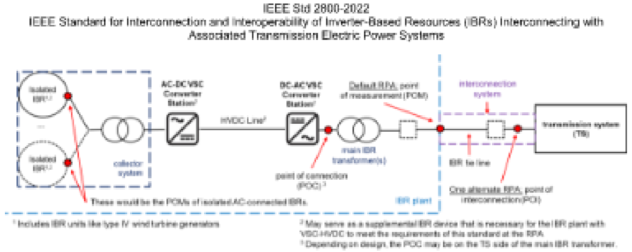
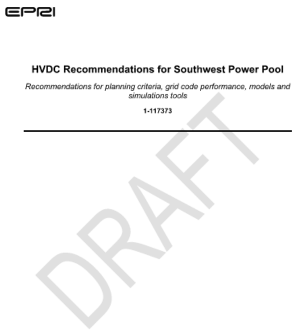
Applicable Codes and Standards

- HVDC converter stations are unique elements (not new but still 😐) in interconnected grid. They are NOT generators (but look like one at inverter end), NOT load (but look like one at rectifier end) and NOT just a simple transmission line (but that's what they are doing)
- Almost NO nationwide codes and reliability standards applicable to HVDC converter stations, let alone Multi - Terminal
- Plus, majority of the legacy HVDC converter stations are thyristor based LCC which are very different from VSC – HVDC converter stations
- Recent IEEE 2800 – 2022 std does include VSC – HVDC converter station as long as it integrates ***islanded*** renewables (NOT the case for GBX project, due to connection to SPP)
- OHL based VSC – HVDC with Half Bridge Technology requires special attention
- SPP is working to get a wholistic HVDC criteria working with EPRI. Invenergy along side with Siemens (supplier for GBX) has been working closely with SPP on such





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Indicative Results – Proof of concept ONLY

Chosen Contingencies for the Presentation

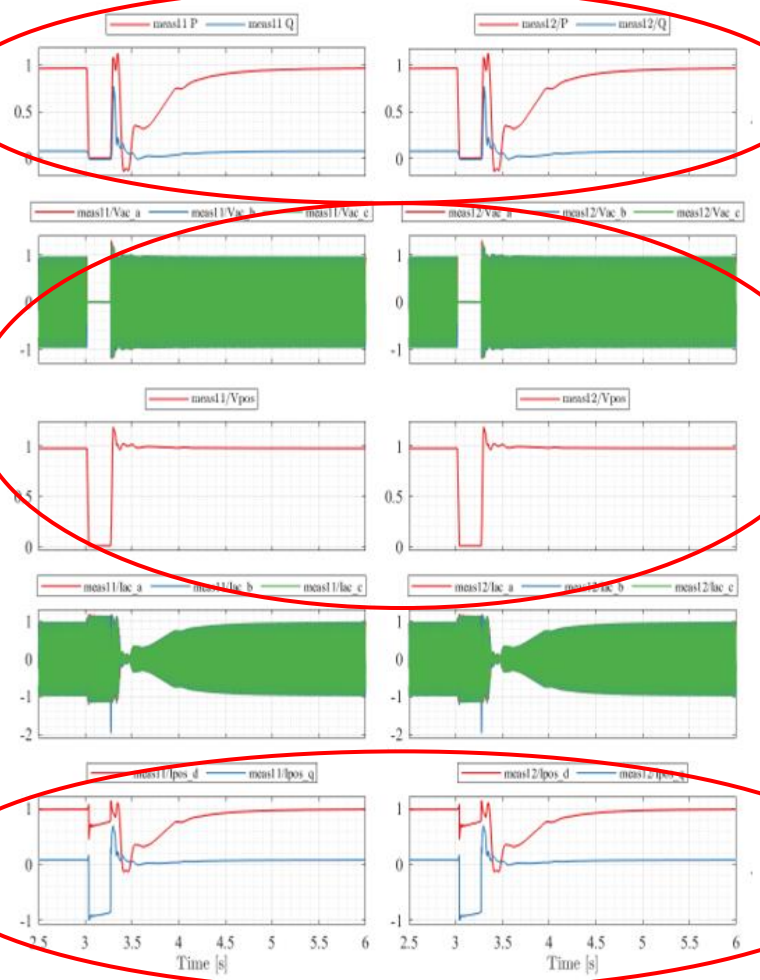
- One three phase to ground fault at inverter end
  - *Basis of selection*:
    - Demonstrate system performance at interconnected grid
    - Demonstrate the efficacy of VSC – HVDC with minimal voltage deviation at rectifier end
- One temporary DC line fault
  - *Basis of selection*:
    - VSC – HVDC with half bridge power module handling temporary DC side fault
    - Insight of impact in surround AC grid with a temporary DC line fault
    - Resuming operation

Very Preliminary findings on Phase 1

Three – Phase to Ground Fault at Inverter Side

Inverter Side Plots

AC voltage at MO goes to ~0



Both positive and negative pole Active power went to ~0, reactive current injection went to almost max to help voltage recovery

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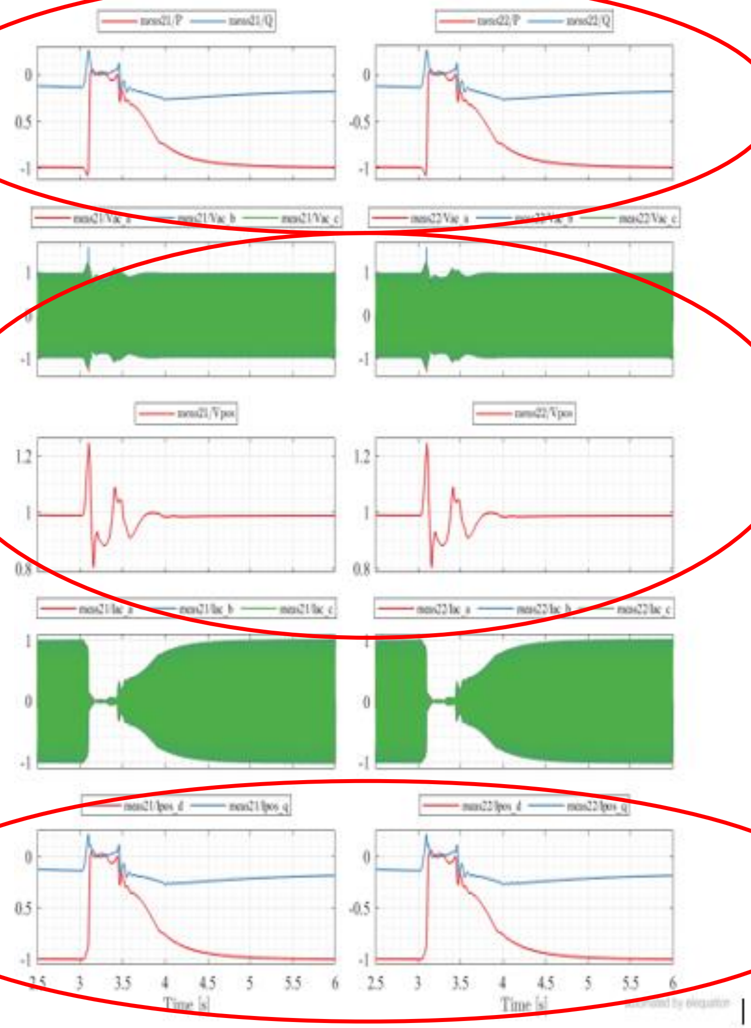
Three – Phase to Ground Fault at Inverter Side

Rectifier Side Plots



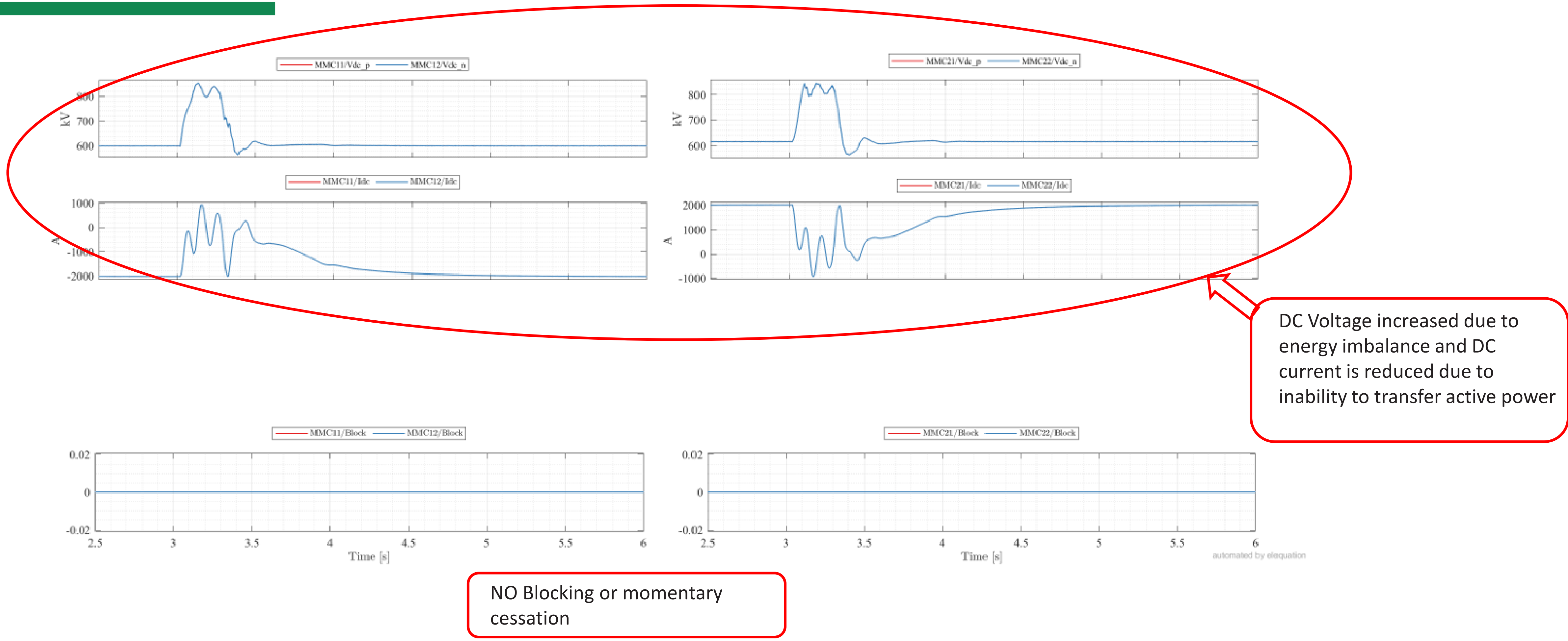
Both positive and negative pole Active power went to ~0, reactive current injection supported to keep AC voltage at rated value

AC voltage at KS sees mild transients

HVDC worked Like a firewall of Voltage Sag

Three – Phase to Ground Fault at Inverter Side

DC Voltage/Current/Blocking Signal



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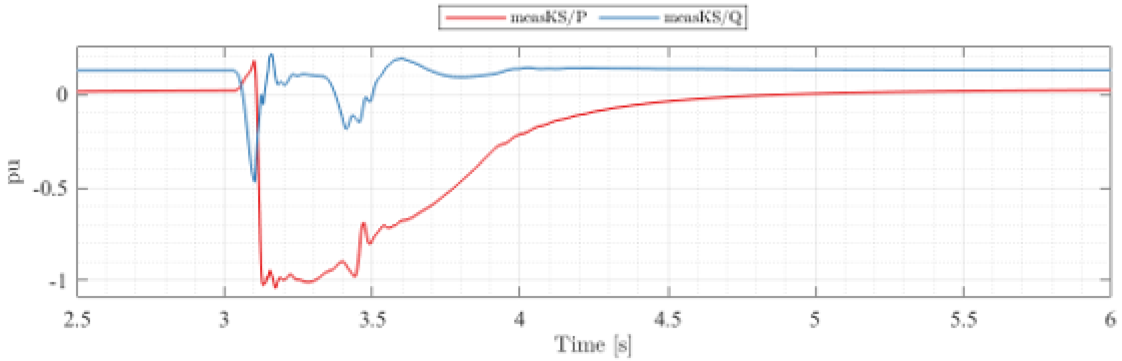
Three – Phase to Ground Fault at Inverter Side

Temporary flow into SPP's grid



Temporary power into SPP's network

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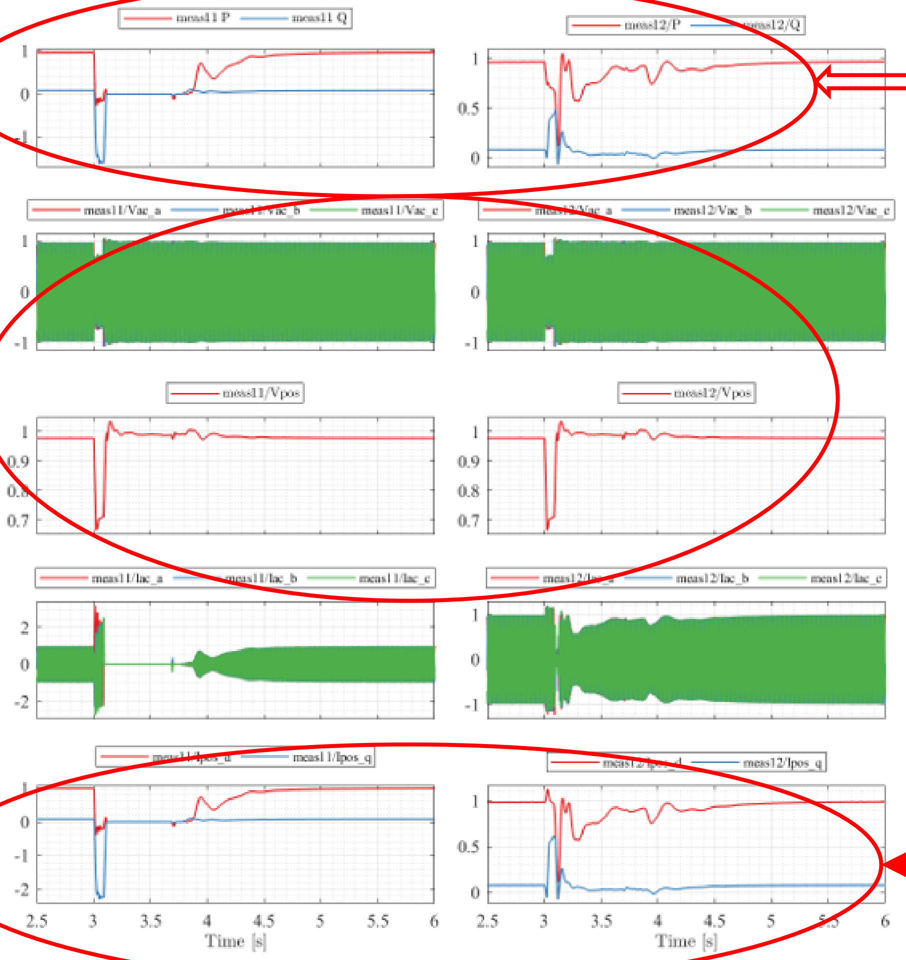
DC Line – Fault (Pos Pole) and Recovery (at Inverter End)

Inverter Side Plots



AC voltage at MO appears to have a high impedance fault with shallow dip

- Positive pole active power goes to zero
- Positive pole feeds fault until AC breakers are opened, resulting AC voltage dip
- Negative pole active power also impacted
- Negative pole reactive power supports AC voltage

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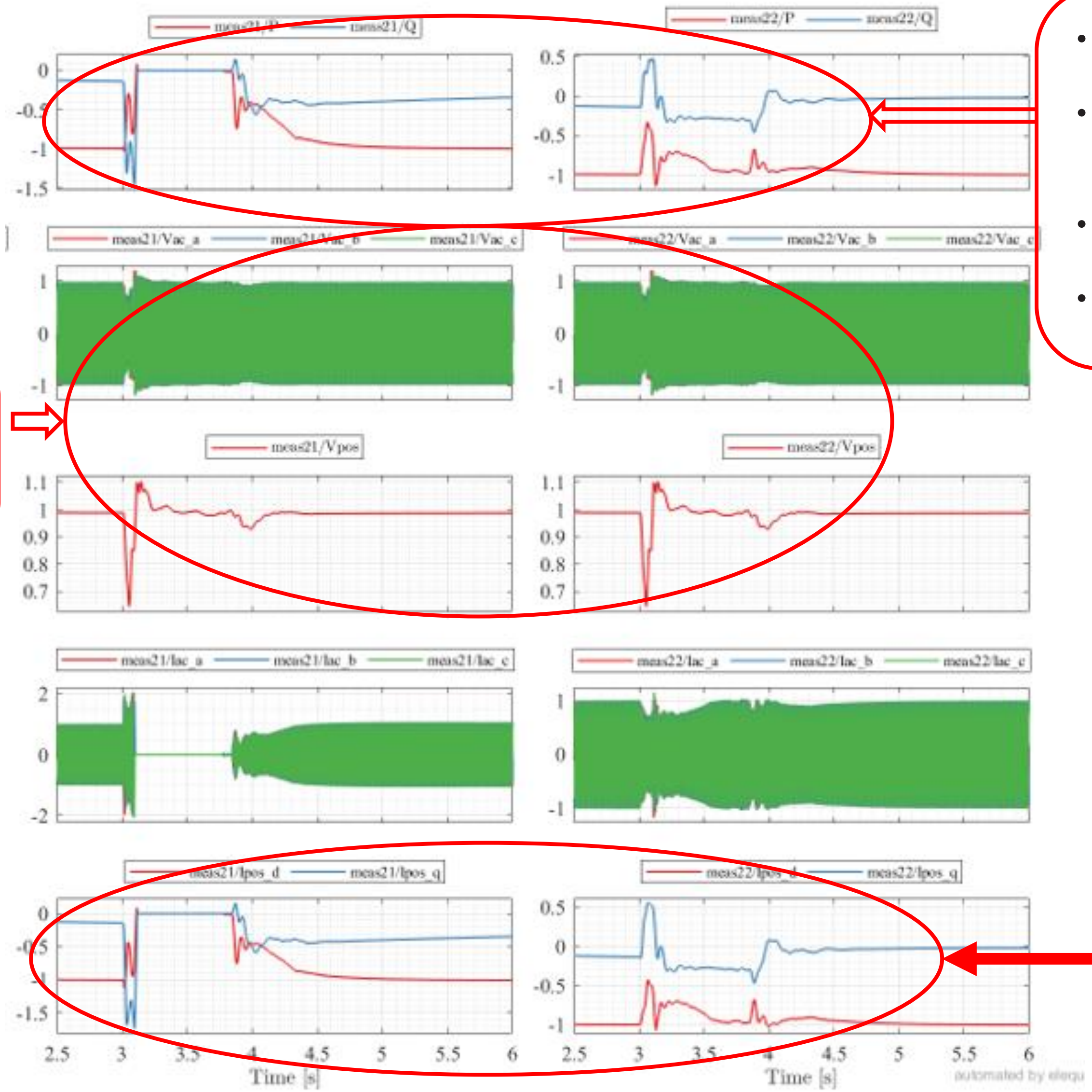
DC Line – Fault (Pos Pole) and Recovery (at Inverter End)

Rectifier Side Plots



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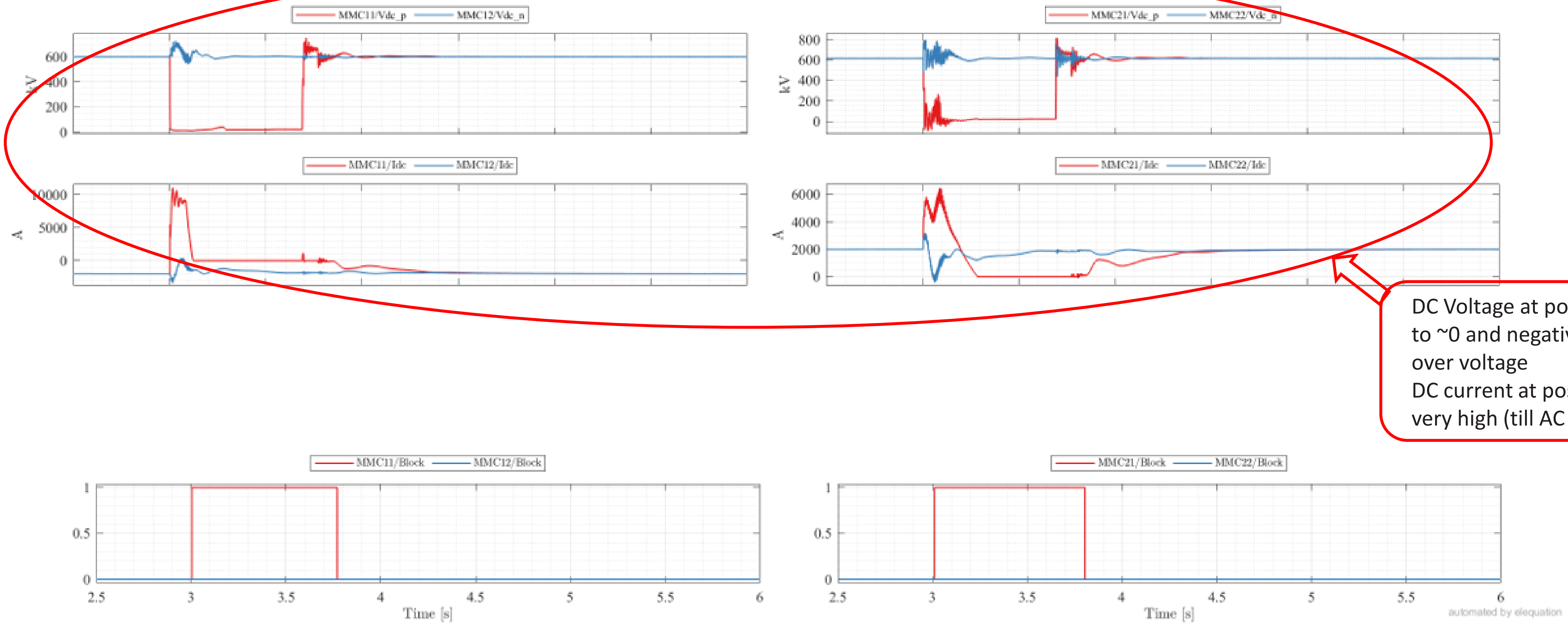

DC Voltage at positive pole goes to ~0 and negative pole sees over voltage
DC current at positive pole goes very high (till AC breakers open)

Positive Pole Converters block

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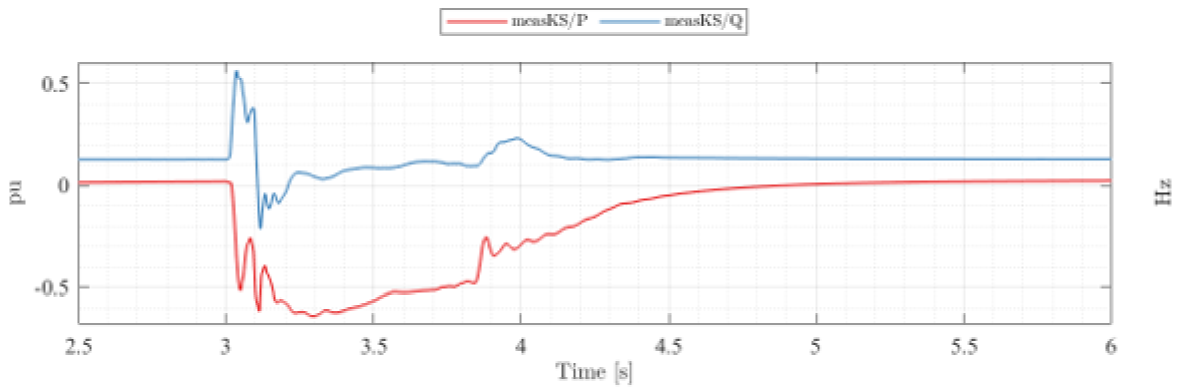
DC Line – Fault (Pos Pole) and Recovery (at Inverter End)

Temporary flow into SPP's grid



Temporary power into SPP's network

Summary and Conclusions

1. Total Delivery Capacity = 5,000 MW
2. Phase 1 (2,500 MW) ⟶ COD Phase 1 2028 – 2029
3. ~740 miles – Multi-terminal (KS, MO, IL/IN)
4. Design work with Siemens commenced and more findings from Siemens will be available towards late CY 2024
5. Multi terminal ***inter-regional*** DC Grids in US will have its unique characteristics:
   1. Predominantly long (several hundreds of miles) over-head lines
   2. Build out with Half Bridge submodules allowing all major OEMs' technology
   3. CANNOT wait for DC breaker to be fully commercially available from all OEMs but should NOT impede introduction of DC breakers at a later time
   4. Finally, grid operators need to take a wholistic view of such buildout not limiting short term benefits of specific regions

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