Scalable Hybrid Large-Scale dc-ac Grid Analysis Methods

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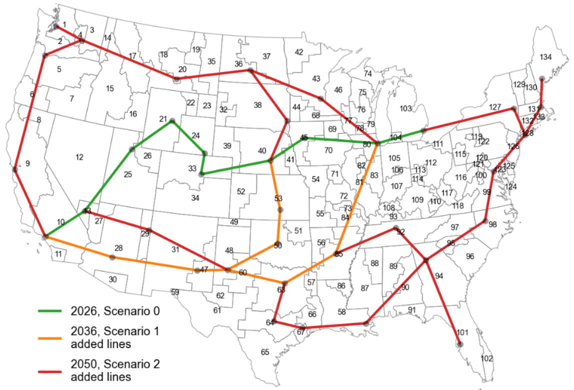
Project Summary: Challenges & Gaps

Gaps	
Simulation Capability	Lack of EMT simulation capability to study dynamics of scalable dc architectures (with 10s of stations).
High-Fidelity Dynamic dc Models	Lack of high-fidelity dynamic models of different dc architectures (meshed MTdc, dc grids) with 10s of stations.
Hybrid dc-ac System Reliability	Lack of understanding of reliability in hybrid ac-dc architectures.
Hybrid EMT-TS Co-Simulation	Scalability of hybrid EMT-TS tools to understand study dynamics of dc-ac architectures has not been evaluated.
Economic Quantification	Lack of tools to accurately characterize the cost-effectiveness of new dc architectures and/or control-protection systems that afford reliability-by-design.
Resilience	Lack of understanding of resilience features and their benefits in dc architectures (eg, capability to transport power during major climate change events like cold weather in Texas).



Example large-scale HVdc system in US

These gaps and challenges have been discussed at **HVdc roadmap** and **moonshot** as well with industry partners

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Project Summary: Objectives

- Develop characterization methods and tools to evaluate reliability, transient stability, and economics of large-scale dc architectures in ac grids

OAK RIDGE National Laboratory

(EMT) PSCAD

High-fidelity HVdc models and nearby ac grid models (based on TS models) to assess HVdc architecture needs (based on ratings obtained from economics) and quantify faster reliability constraints (and provide to economics)

NREL NATIONAL RENEWABLE ENERGY LABORATORY

(Economics) ReEDS/PLEXOS

Optimization to identify economic HVdc infrastructure in US and quantify resilience and reliability constraints (that are provided from EMT and TS dynamics)

Pacific Northwest NATIONAL LABORATORY

(TS) PSSE

ac system dynamic models to quantify system impact from HVdc systems (based on EMT models provided) and characterize slower reliability constraints (and provide to economics)

The Numbers

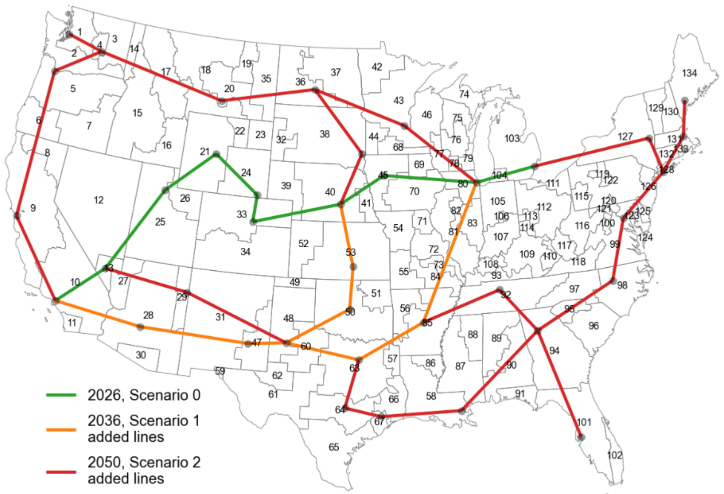
- DOE PROGRAM OFFICE:
  OE – Transformer Resilience and Advanced Components (TRAC)
- FUNDING OPPORTUNITY:
  N/A
- LOCATION:
  Knoxville, TN; Denver, CO; Richland & Seattle, WA
- PROJECT TERM:
  10/01/2021 to 01/31/2025
- PROJECT STATUS:
  Ongoing
- AWARD AMOUNT (DOE CONTRIBUTION):
  $2,888,000
- AWARDEE CONTRIBUTION (COST SHARE):
  N/A
- PARTNERS:
  ORNL, NREL, PNNL

Technical Approach

- Economic benefits quantification of dc architectures
- Advanced fast-acting control in HVdc substations for improved reliability
- High-fidelity EMT models of dc scenarios (with specialized numerical simulation algorithms)
- Scalable hybrid simulation of PSCAD-PSSE (EMT and TS dynamics) through E-TRAN

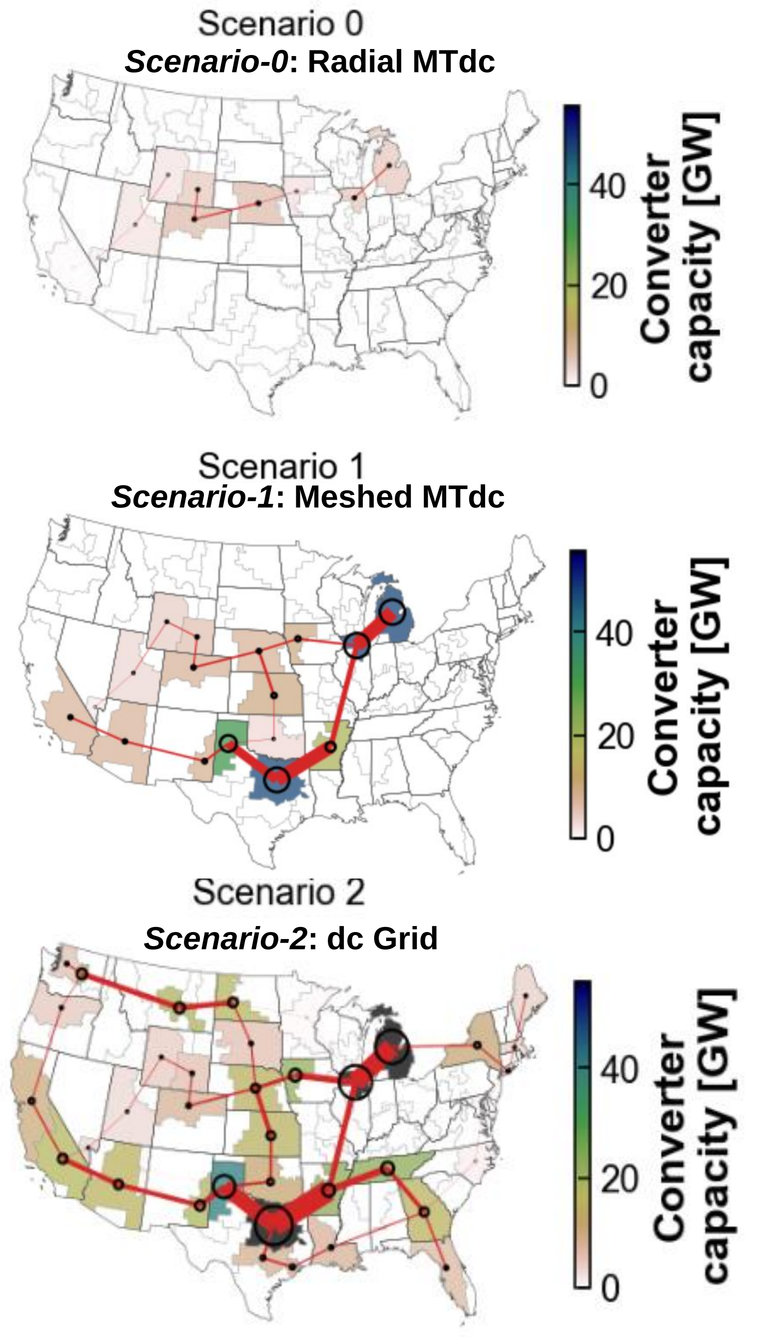
Accomplishments

- **Scenarios:** Develop MTdc architectures for 2026-2030 (near-term), 2036 (medium-term), and 2050 (long-term)
  - Addressing the gap lack of tools to quantify economic benefits of dc architectures
- **Model:** Develop Capacity Expansion Model (CEM)
- **Software Used:** ReEDS
- **Major Accomplishments:** Scenarios developed (scenarios 0, 1, 2) – shown in the right images)

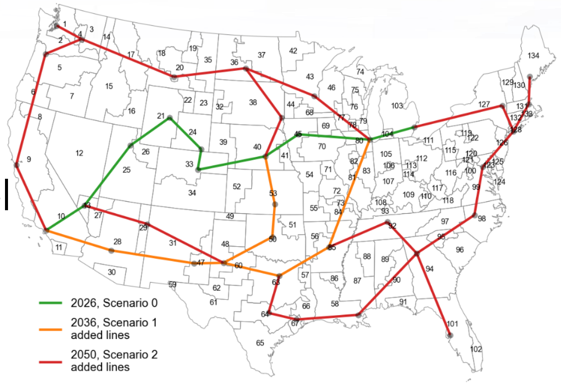


Scenario	Renewable Generation %
2026 (S0)	26.51%
2036 (S1)	82.88%
2050 (S2)	88.00%

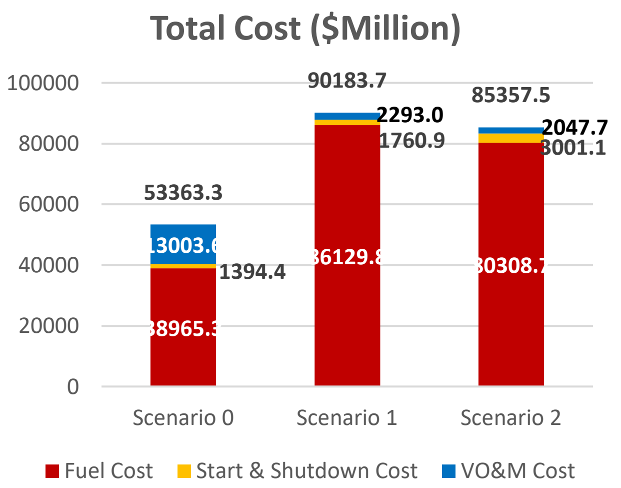
Large-scale dc architectures identified based on economic benefits

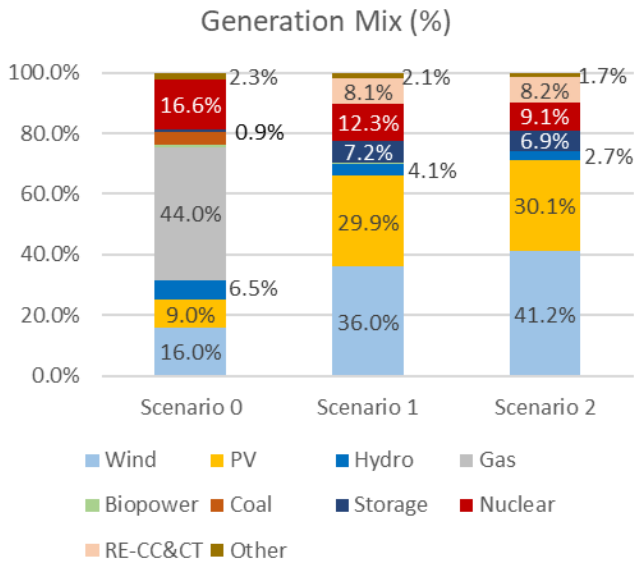


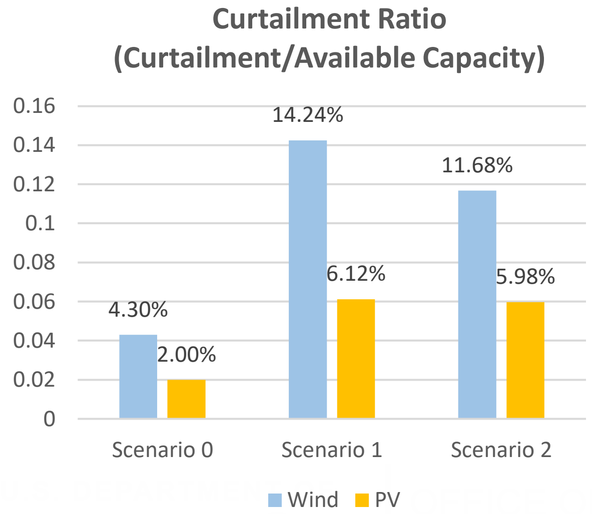
Accomplishments



- **Scenarios Analyzed:** Quantify benefits of the three scenarios developed
  - Addressing the gap lack of tools to quantify economic benefits of dc architectures
- **Models:** MTdc Regional-to-Nodal optimal VSC siting model linkage in production cost model (PCM) using NARIS database
- **Software Used:** PLEXOS
- **Major Accomplishments:** Operating costs, benefits identified along with generation mix and VRE curtailment shown below







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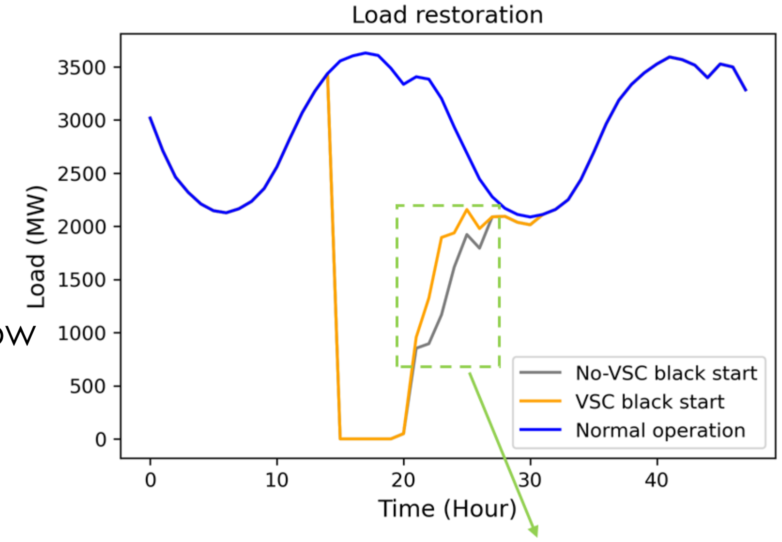
Accomplishments

- **Use Case Analyzed**: VSC blackstart support strategy in PCM (resilience)
  - **Models:** Develop 2011 Southwest Blackout with Scenario 0 VSC in NARIS using PLEXOS
  - **Major Accomplishments:** Blackstart strategy with VSC and resilience support benefits
- **Use Case Analyzed:** VSC phase angle damping support constraints in security constrained unit commitment (SCUC)
  - **Major Accomplishments**: Equivalent VSC phase angle damping support AC power flow constraints in SCUC



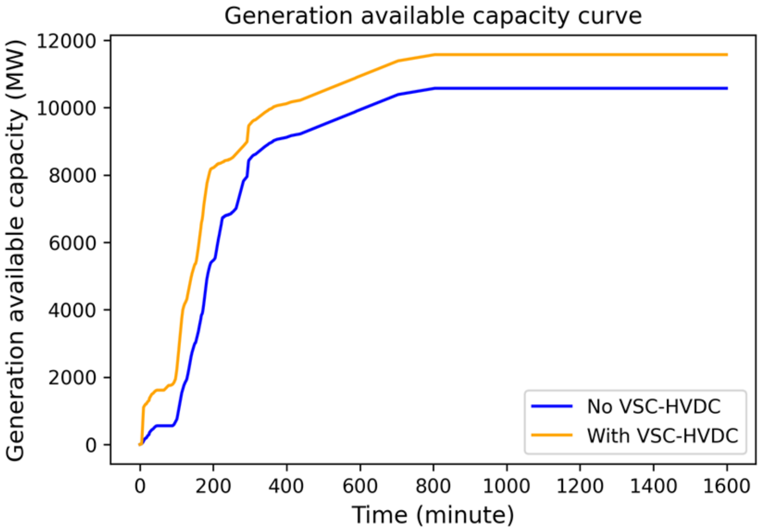
Phase angle damping constraints

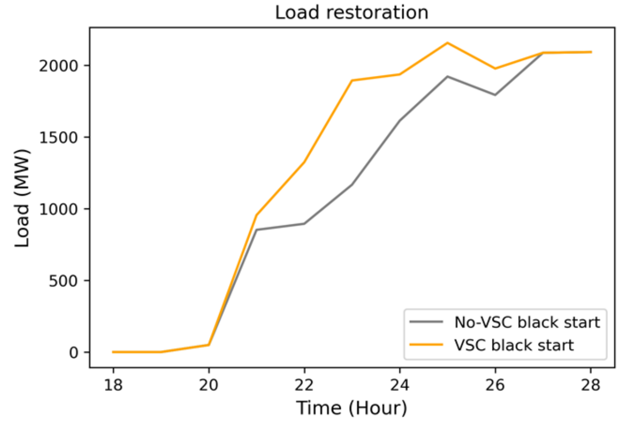
A modal damping ratio 10% was specified to ensure that the modes settle within 10 s.

$$\frac{1}{2}K_d\sqrt{\frac{\omega_s}{2H\cdot P_{max}\cdot\cos\delta_0}}\geq 10\%$$

The power flow constraint on AC transmission line is then formulated as:

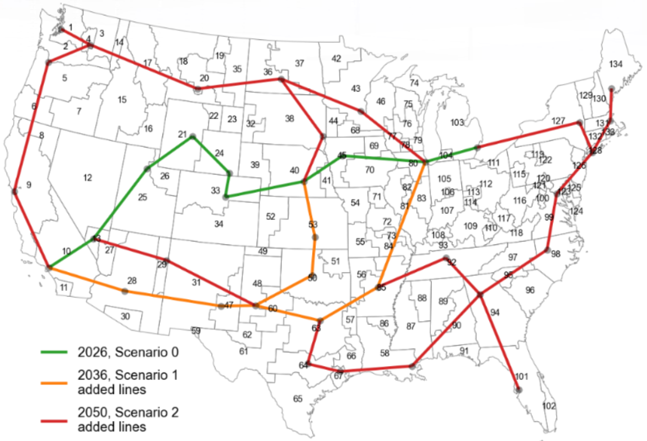
$$P_{max}\leq\frac{15\cdot {K_d}^2\,\omega_s}{H\cdot\cos\delta_0}$$





Accomplishments

- **Scenario Analyzed:** Analyze *scenario-0* in detail to provide an understanding of HVdc architecture needed to ensure reliable and economic operation
  - MTdc station architecture for radial system.
  - Addressing the gap lack of understanding of reliability in hybrid ac-dc architectures.
- **Model Used:** EMT models were used
  - High-fidelity models from SHIFT-PE library of HVdc stations using switched system model of all modules present within each HVdc station.
  - High-fidelity model of dc breakers developed.
- **Software Used:** PSCAD, Fortran



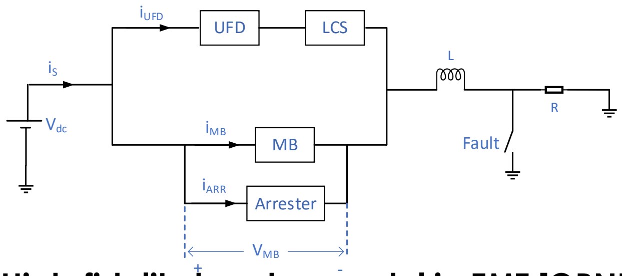
***Scenario-0*: Meshed MTdc (green) [NREL]**

S. No	City	Region	HVDC station Capacity (MW)
1	Los Angeles, CA	p10	186
2	Las Vegas, NV	p13	2338
3	Salt Lake, UT	p25	2465
4	Shoshoni, WY	p21	3381
5	Cheyyenne, WY	p24	4579
6	Denver, CO	p33	5744
7	Grand Island, NE	p40	5744
8	Fort Dodge, IA	p45	2071
9	Chicago, IL	p80	4468
10	Detroit, MI	p103	4468

Lower power ratings

Higher power ratings

***Scenario-0*: Power rating of each station [NREL]**



High-fidelity breaker model in EMT [ORNL]

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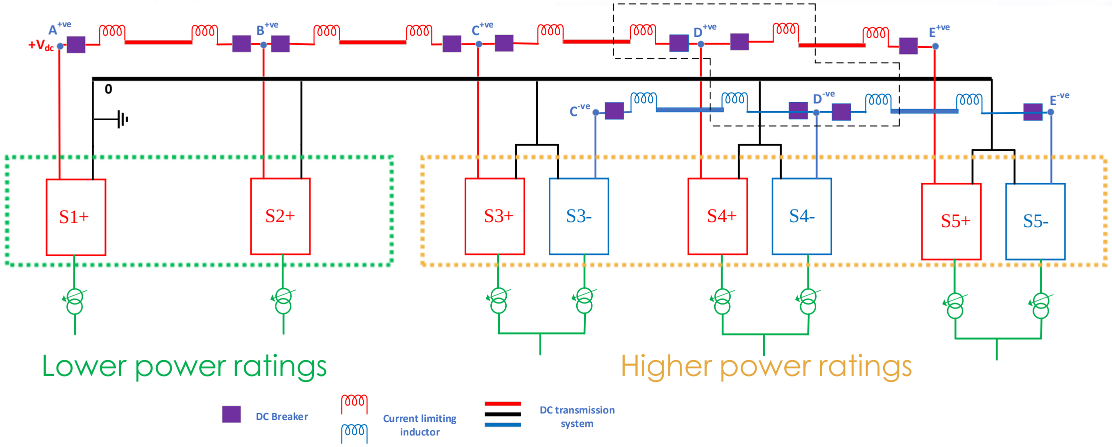
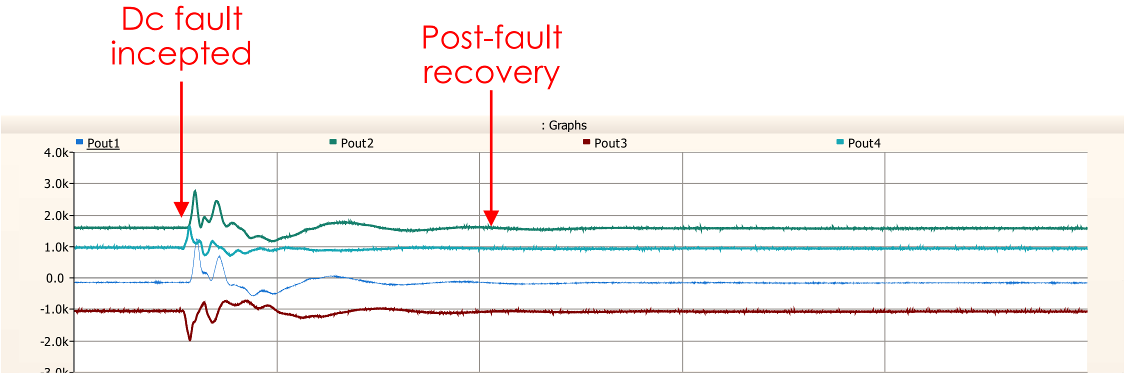
Accomplishments

- **Major Accomplishments:**
  - Novel symmetric bipole and asymmetric monopole HVdc system architecture with protection developed for reliable and economic operations.
  - Placement of dc breakers considered to protect from dc faults and ensure continuity of operation during faults with minimum disruptions.
  - Assessment of coordination needed to ensure continuity of operation during faults.
- **Deductions:**
  - Hybrid symmetric and asymmetric HVdc architecture is feasible in steady-state and in dynamics.
  - Fast coordination is necessary between HVdc stations nearby and with dc breakers in vicinity.



Mixed symmetric bipole and asymmetric monopole reliable HVdc architecture [ORNL]

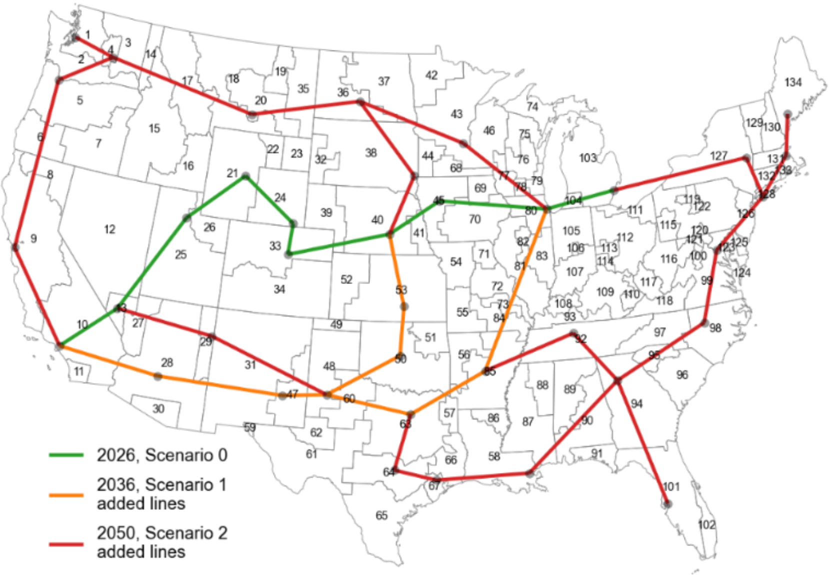


Asymmetric monopole's response to dc fault: Stable operation post-fault observed [ORNL]

New MTdc system architectures evaluated based on economics of the system design needs

Accomplishments

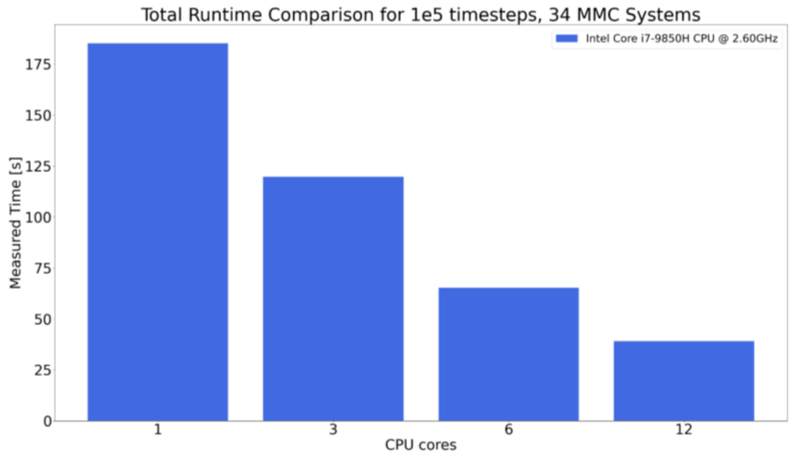
- **Scenario Considered:** Develop scalable dc simulation models in EMT with high-fidelity models of HVdc systems (stations, breakers, lines) for *scenario-1*
  - Simulation algorithms and HPC techniques explored.
  - Addressing the gap lack of high-fidelity dynamic models of different dc architectures (meshed MTdc, dc grids) with 10s of stations.
- **Requirement:** Compatibility of developed models in standard EMT simulator (e.g., PSCAD)
- **Algorithms:** EMT simulation algorithms and parallel computing
  - Numerical stiffness-based hybrid discretization.
  - Software engineering practices for optimum parallelism.

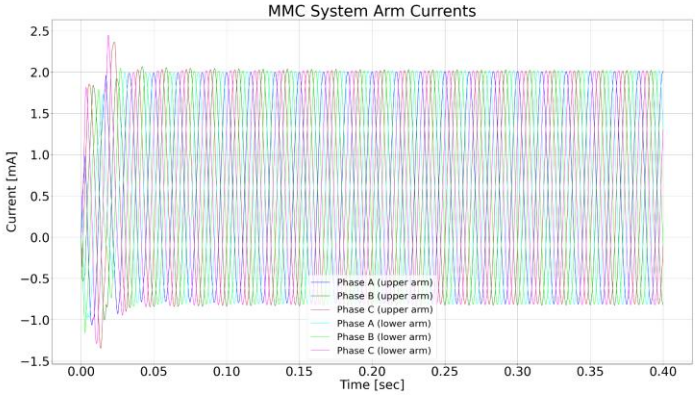


***Scenario-1*: Meshed MTdc (green + orange) [NREL]**

Accomplishments

- **Software Used:** PSCAD, Fortran, C
- **Major Accomplishments:**
  - **34 MMC stations** have been simulated in parallel to mimic bipole architecture in *scenario-1*.
  - Up to **6x speed-up** observed.
  - Greater than **2x scalability** in the number of dc stations modeled.
- **Deductions:**
  - Scalability of HVdc systems in EMT analysis is feasible and can be an enabler to study coordination of HVdc stations across US.
  - Improved simulation algorithms and HPC techniques can assist with the scalability.



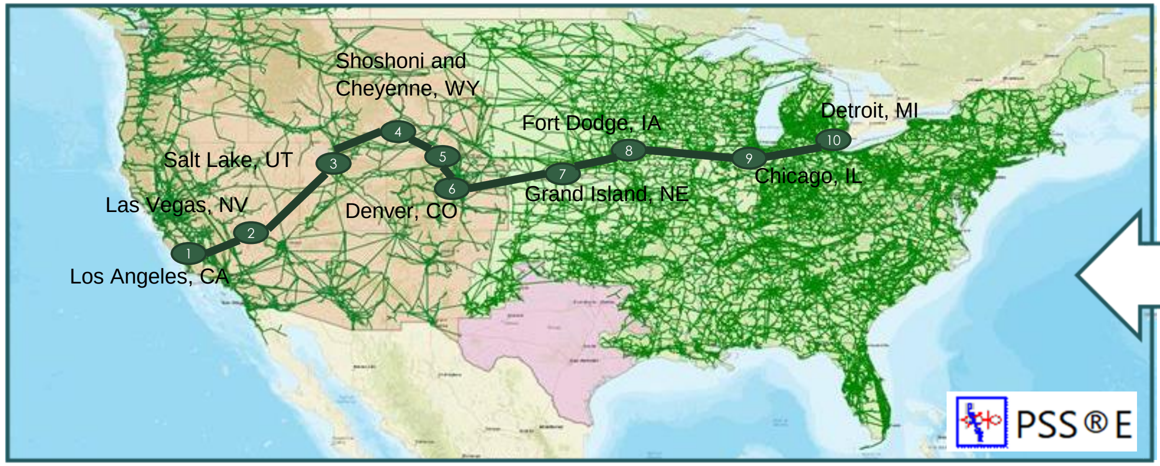


High-fidelity models and HPC-based EMT simulation of large-scale dc substations [ORNL]

Speed-up observed with multi-core usage enables use of more MMC substations – of the order of 34 (with greater than 2x scalability)

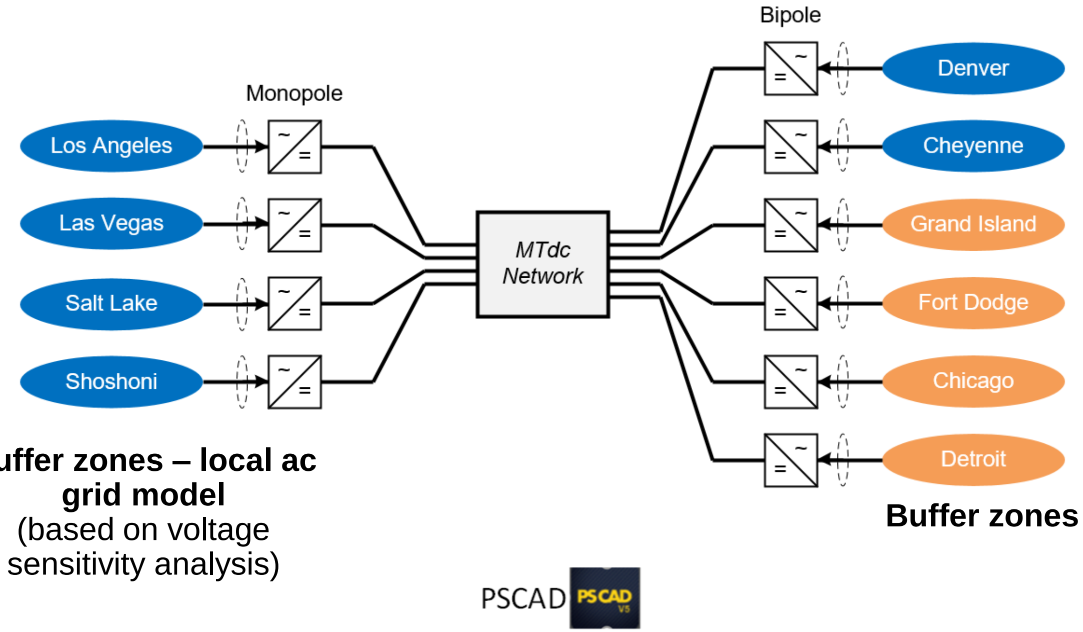
Accomplishments

- **Scenario:** Scenario-0 is analyzed for faults in ac grid in EMT-TS for ac grid faults
  - Addressing reliability understanding in hybrid ac-dc architectures
- **Model:** High-fidelity MTdc system model and local ac grid model (buffer zones) in PSCAD with WECC HS 2031 and EI HS 2030 in PSSE [PNNL-ORNL]
- **Software:** PSCAD, PSSE, E-Tran



Scenario-0: **10-terminal radial MTdc grid (green) [NREL]**

E-Tran

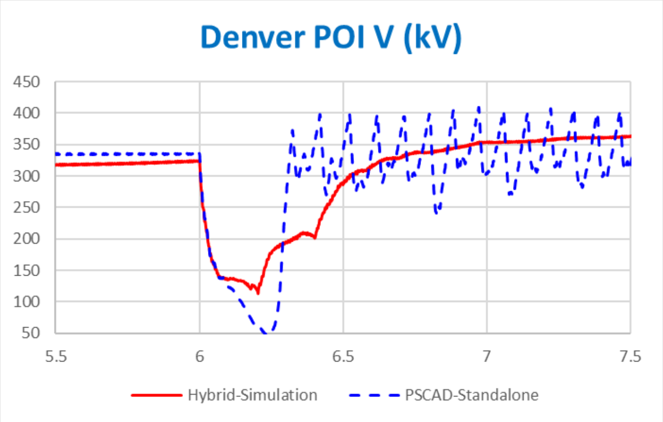


Accomplishments

- **Major Accomplishments:**
  - High-fidelity EMT-TS co-simulation result for ac faults in different locations in WI and EI sides
  - Good compatibility between full EMT and co-simulation is observed once controllers are slowed down

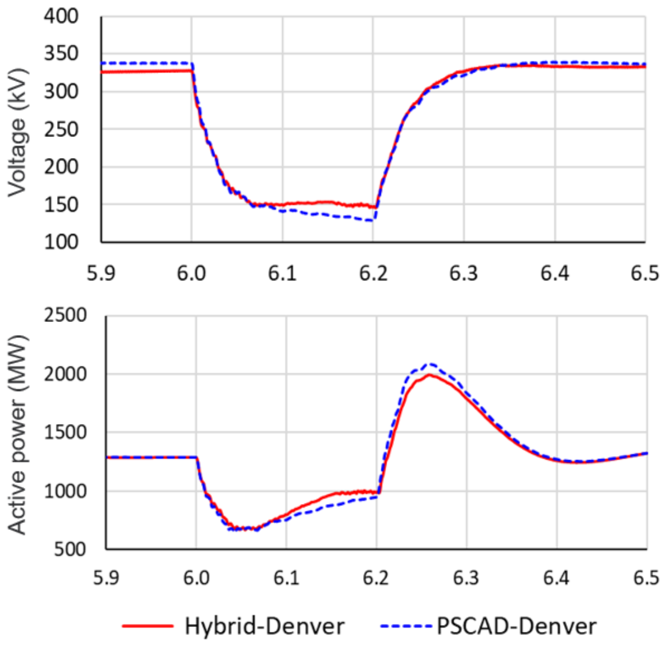
Deductions:

- Improved simulation algorithms and HPC techniques can assist with the scalability.

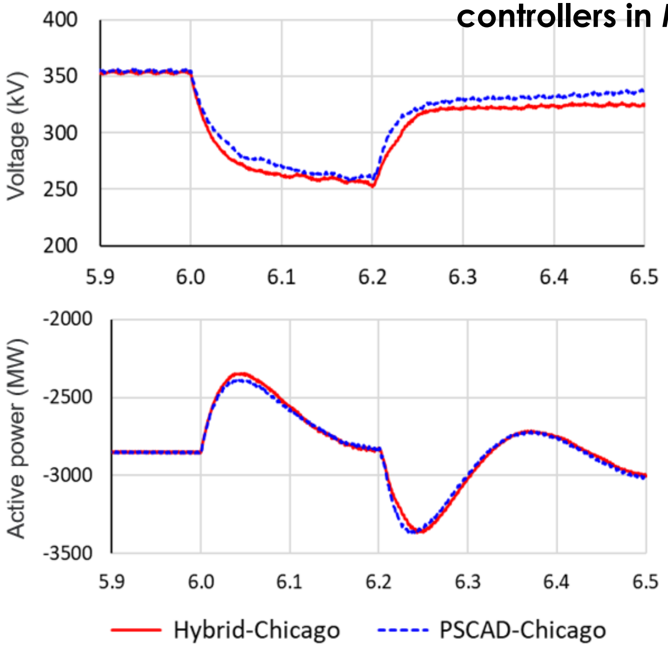


Use case with faster controllers in MTdc

Denver POI



Chicago POI



Use case with slower controllers in MTdc

Scalable EMT-TS co-simulation with 10 substations in EMT (PSCAD) & TS (PSSE) co-simulation of EI and WI grids

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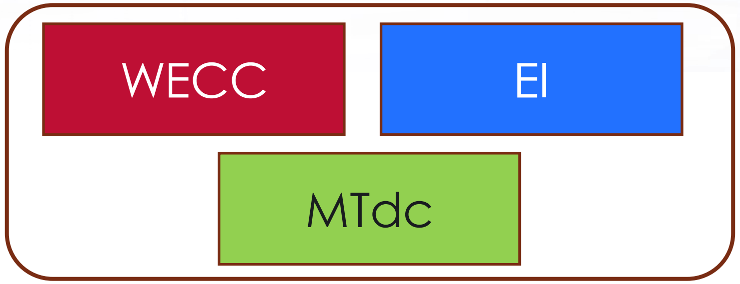
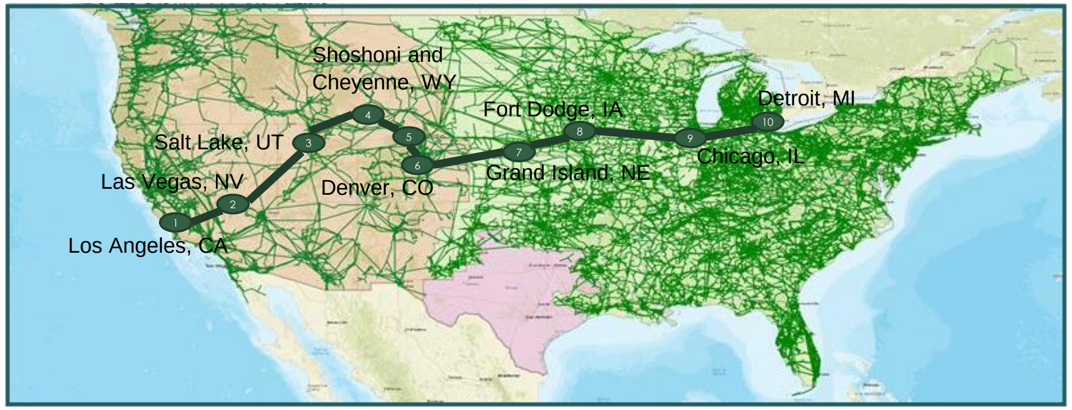
Accomplishments

- **Scenario:** Scenario-0 is analyzed for loss of generation in ac grid in TS
  - Addressing reliability understanding in hybrid ac-dc architectures
- **Model:** Continental modeling
  - Numerical AC-DC power flow (WECC HS 2031 and EI HS 2030) [PNNL]
  - TS dynamics in phasor domain for an MTdc grid [PNNL]
- **Software:** PSSE, Fortran

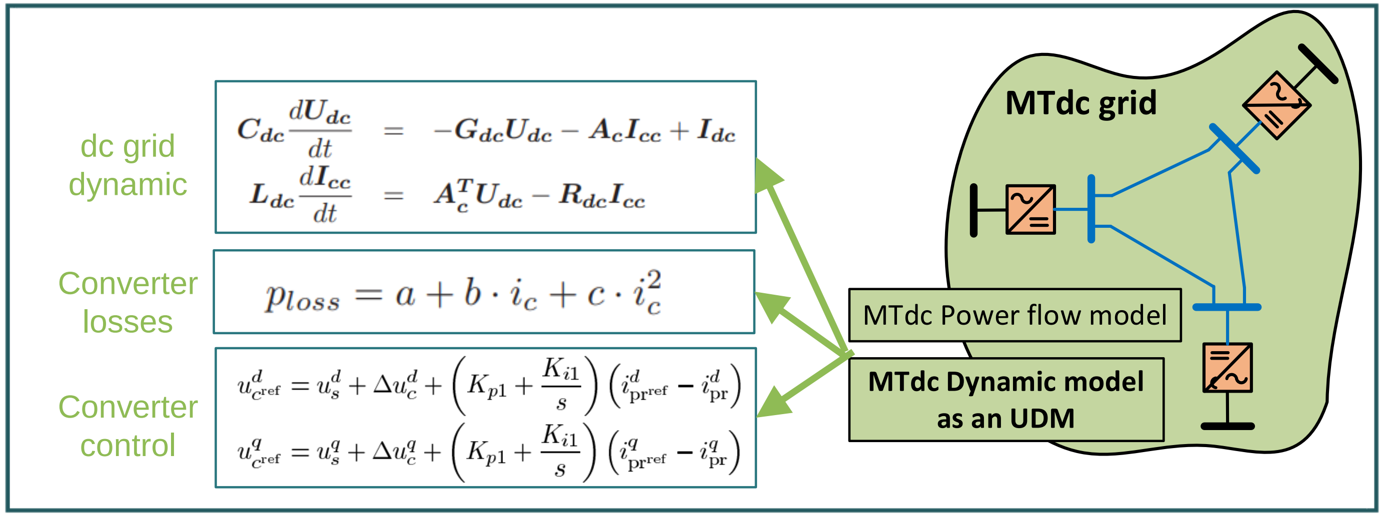


Combined TS model



Inter-regional power flow and TS models established for scenario-0

- Max POI injection 3,666 MW (Chicago)



dc grid dynamic

$$\begin{aligned} C_{dc}\frac{dU_{dc}}{dt} &= -G_{dc}U_{dc} - A_cI_{cc} + I_{dc} \\ L_{dc}\frac{dI_{cc}}{dt} &= A_c^TU_{dc} - R_{dc}I_{cc} \end{aligned}$$

Converter losses

$$p_{loss} = a + b\cdot i_c + c\cdot i_c^2$$

Converter control

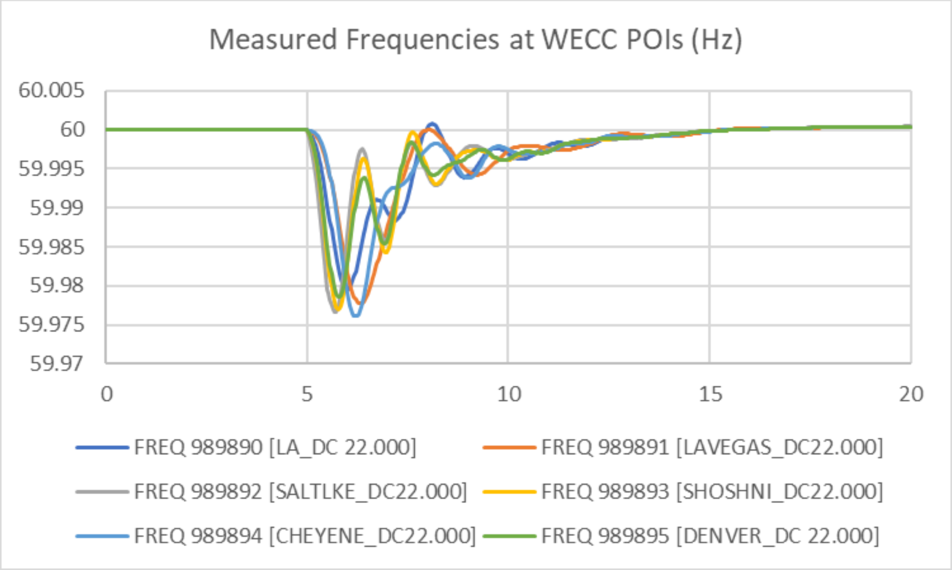
$$\begin{aligned} u_{cref}^d &= u_s^d + \Delta u_c^d + \left(K_{p1} + \frac{K_{i1}}{s}\right)\left(i_{\text{pref}}^d - i_{\text{pr}}^d\right) \\ u_{cref}^q &= u_s^q + \Delta u_c^q + \left(K_{p1} + \frac{K_{i1}}{s}\right)\left(i_{\text{pref}}^q - i_{\text{pr}}^q\right) \end{aligned}$$

TS model of dc systems

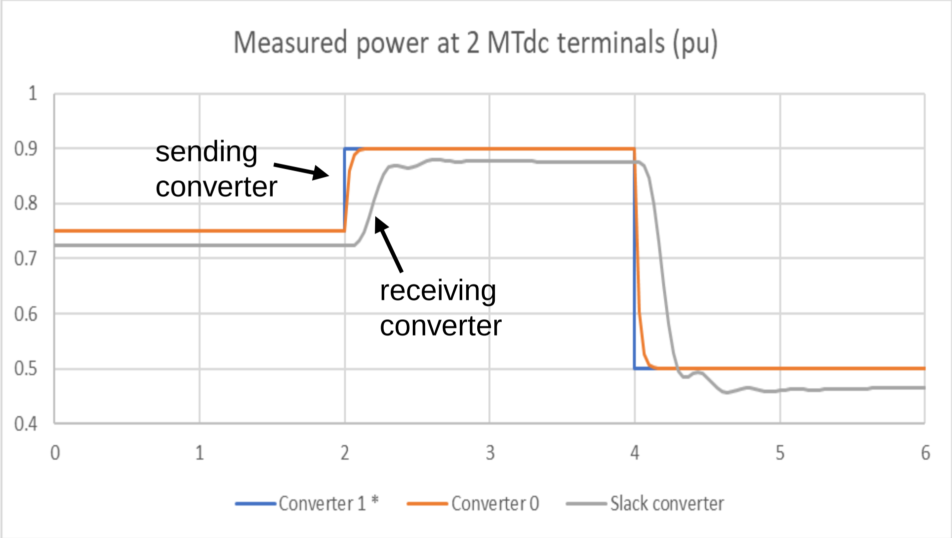
Accomplishments

- **Major Accomplishments:**
  - Full steady-state and TS model of an MTdc grid at **full WECC & EI** interconnection level
  - **Grid forming** and grid following control are developed options for MTdc converters
  - Up to **30x speed-up** observed, compared to EMT-TS co-simulation

- **Deductions:**
  - Able to model different MTdc grid topologies (monopolar/bipolar) and number of terminals
  - Flexible to develop and study different converter controls and grid supporting functions (voltage and frequency support)



System frequency during contigency (Chief Joseph insertion – 1.3 GW load increase near Grand Coulee)



Real power control capability (receiving-end terminal reflects the power setpoint change at the sending-end terminal)

TS dynamic model for MTdc system developed

Timeline: Milestones

Milestone (or Decision Point)	Status
ORNL, PNNL, NREL: Identify 2 scenarios of MTdc architectures (meshed, grids) of interest for integrating renewables and connecting asynchronous US power grids	Completed
ORNL: Develop 1 component model (breakers).	Completed
NREL: Develop 3 scenarios of capacity expansion models.	Completed
PNNL: Develop continental-level ac power flows for scenario 0.	Completed
ORNL: Preliminary control algorithms test on scenario 0.	Completed
Go/No-Go (PNNL): Develop MTdc TS-based dynamic models for scenario 0.	Completed
Go/No-Go (ORNL): Up to 2x scalability in the dynamic models developed for dc architectures with submodule to systems dynamics. (Develop scenario 1 model with advanced simulation algorithms for 2x scalability.)	Completed
Go/No-Go (ORNL): Showcase the benefits of radial MTdc in scenario 0 through fast control response in one use case. (Develop control algorithms in scenario 0 for reliable operations. Inform the research community and industry on library of ac-dc models and ac-dc simulation algorithms.)	Completed.
Go/No-Go (NREL): Successfully deliver a list of extreme event models in PCM.	Completed.
Go/No-Go (PNNL, ORNL): Successfully configure and test hybrid EMT-TS simulation for scenario 0.	Completed.

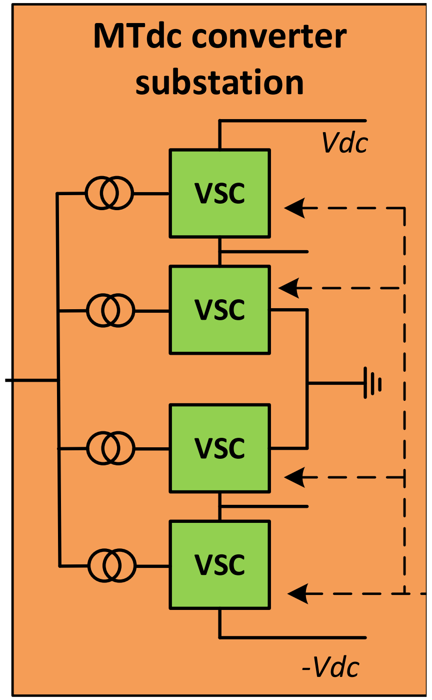
Timeline: Risk & Mitigation

Risk	Mitigation Strategy	Status (New, Emerging, Realized, Mitigated)
ac system may not be able to take the dc system injections, which may require significant effort to identify associated ac upgrades.	The lab teams can develop mitigation measures around simplification on determining ac upgrades of the base case to accommodate dc injections or selecting lower dc system capacity depending on available ac capability, as well as careful selection of dc-ac injection points. Model, validate, and refine chosen locations in continental level ac power flow models in PSSE. Leverage previous experience at PNNL and NREL.	Mitigated
Based on previous work for TRAC program, there is a risk that EI and WI grid models might not work together due to limitations in ETRAN software for EMT-TS hybrid simulations.	PNNL can work with Siemens and/or Electranix support team to resolve this issue. If it turns out that EI and WI cannot be simulated together in ETRAN, PNNL and ORNL will consider analyzing interconnections separately focusing on one interconnection at a time and/or using equivalent or reduced-order models (eg, one-machine dynamic grid model) for the interconnection that is not part of the main focus.	Mitigated
Scalability of scenario 1 in existing simulators may be a challenge due to stability of the implementation within the simulators (PSCAD)	Custom codes developed and integrated (tested with dlls or C code) to the simulators will be utilized to enable scalability.	Mitigated

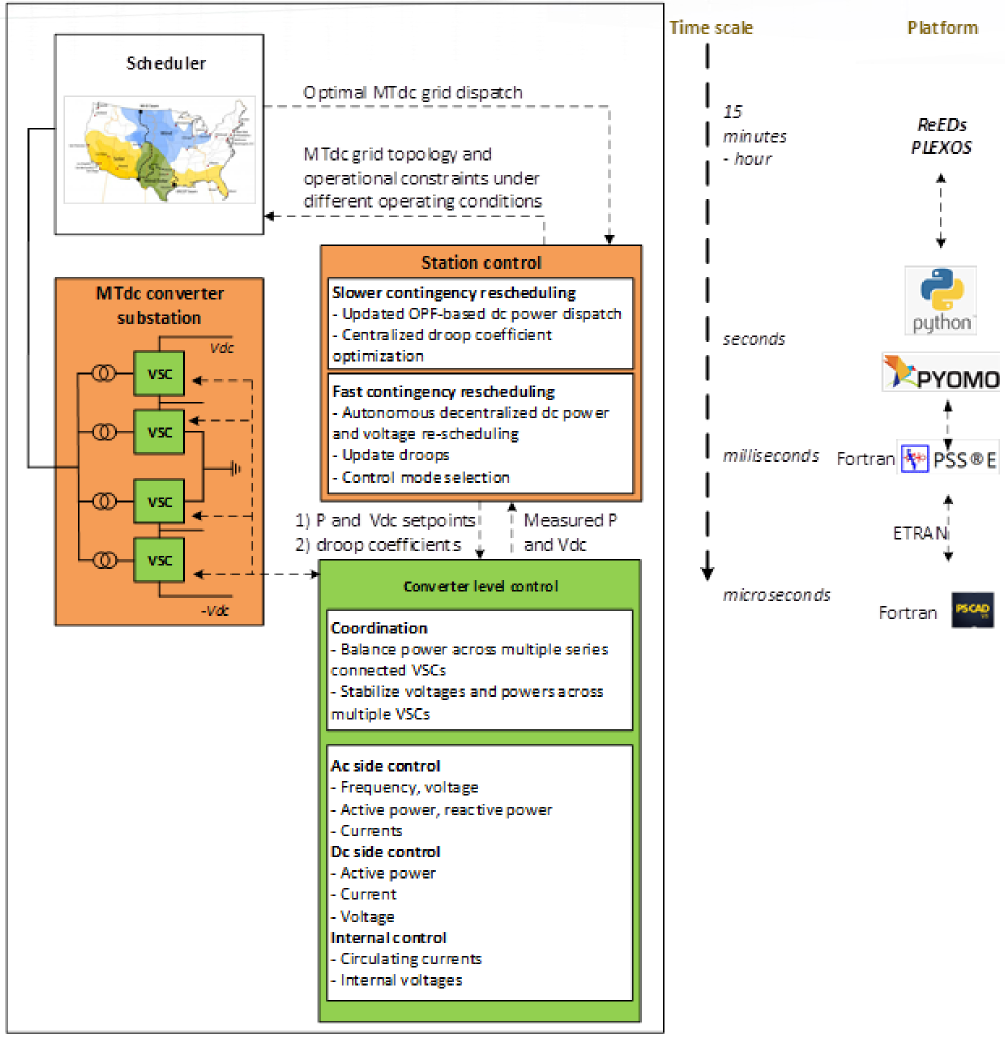
Impact/Commercialization

- **List of innovations**
  - Symmetric-asymmetric MTdc architecture [ORNL] – *submitted as an invention disclosure*
  - Scalable MTdc converters simulation [ORNL]
  - Three scenarios for MTdc in future power grids [NREL]
  - Black-start procedure with MTdc [NREL]
  - TS model of MTdc [PNNL]
  - Scalable EMT-TS co-simulation with MTdc [PNNL, ORNL]

Future Work



Higher power rated HVdc station



Control and protection system architecture for higher power rated HVdc

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Future Work

Years 2 & 3 Project Objectives:

- ORNL:
  - New MTdc topologies for high power rating
  - Control and protection for new MTdc topologies (converter and local controls in protection): use cases include dc faults, ac faults, disconnection/connection procedure (maintenance)
  - Hierarchical control and protection system evaluation (in collaboration with PNNL, NREL)
- PNNL:
  - Station controls (voltage, frequency, mode selection)
  - Droop optimization and selection; Fast re-scheduling during events
  - Hierarchical control and protection system evaluation (in collaboration with ORNL, NREL)
- NREL:
  - Optimal power flow
  - Real-time optimal re-dispatch post events (in slower timescale)
  - Hierarchical control and protection system evaluation (in collaboration with ORNL, PNNL)

THANK YOU

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Backup Slides

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Acronyms

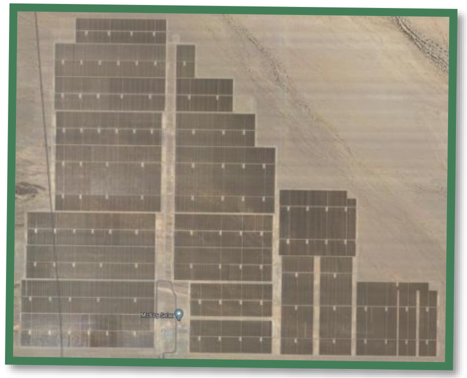
- ORNL – Oak Ridge National Laboratory
- PNNL – Pacific Northwest National Laboratory
- NREL – National Renewable Energy Laboratory
- dc – direct current
- ac – alternating current
- EMT – Electromagnetic Transient
- TS – Transient Stability
- MTdc – Multi-Terminal direct current
- HVdc – High-Voltage direct current
- MMC – Modular Multilevel Converter
- EI – Eastern Interconnection
- WI – Western Interconnection
- PCM – Production Cost Model
- VSC – Voltage Source Converters
- SHIFT-PE – Suite of high-fidelity

Suite of High-Fidelity EMT Time-Domain Models of Large-Scale PEs (SHIFT-PE)

Capability: Fast simulation of ***high-fidelity dynamic models*** of large-scale PEs and PE-grids (towards packaged capability)

Approach: Advanced numerical simulation algorithms that enable speed-up and maintain accuracy

Usage: For designers and planners to study future power grids (and for post-mortem analysis) – ***enabler for grid modernization and integration of emerging energy sources***

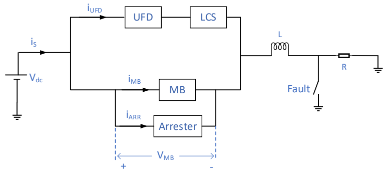


PV Power Plant (100s of inverters, 10s – 1,000 MW)

HVdc Substation (2,400 PE modules, 100 – 3,000 MW)

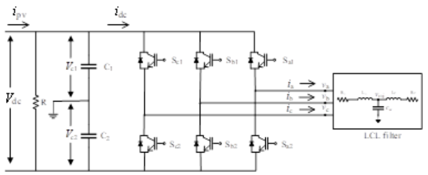
Hybrid Plant (1,500 PE modules, 100 – 2,000 MW)

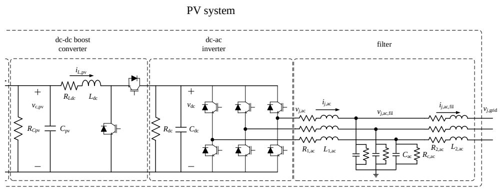
EV Charging Stations (300 chargers in T&D grid)

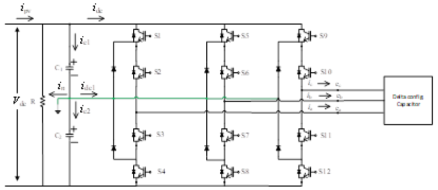


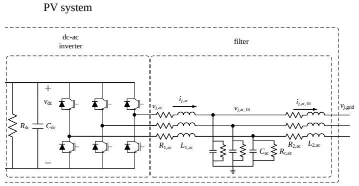
HVdc breaker

Library of high-fidelity dynamic models of large-scale PE systems with advanced simulation algorithms with up to 17,000x speed-up observed









Library of PE component models (basic building block of PE systems)

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