EMT & EMT-TS Hybrid Simulation: HVdc Scenarios Planning in US

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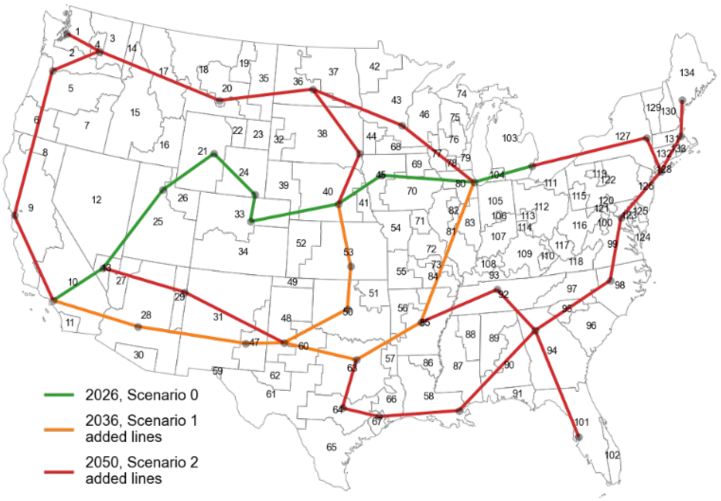
ORNL is managed by UT-Battelle, LLC for the US Department of Energy

Introduction

- Large penetration of HVdc expected
  - Regional interconnectivity for reliability/resilience
  - Transfer generation to load centers
  - Offshore grid
- Drivers
  - Reduced energy storage needs
  - Reliability/resilience needs



Scenarios

HVdc – High Voltage direct current

Gaps w/ Analyzing Large-Scale DC Systems in US

Tools & Analysis	
dc System Reliability	EMT simulation of high-fidelity models of dc architectures to assess reliability (dc-side) and identify control & protection needs
Hybrid dc-ac System Reliability	EMT-TS co-simulation to evaluate the interaction of dc architectures with ac-side (events impacting reliability)
Economic Quantification	Capacity expansion and production cost modeling tools that assist with identification of economic dc architectures and benefits of control & protection
Resilience	Production cost modeling tools assisting with assessing the impact of dc architectures on resilience in power grid (e.g., black start, impact of damping)

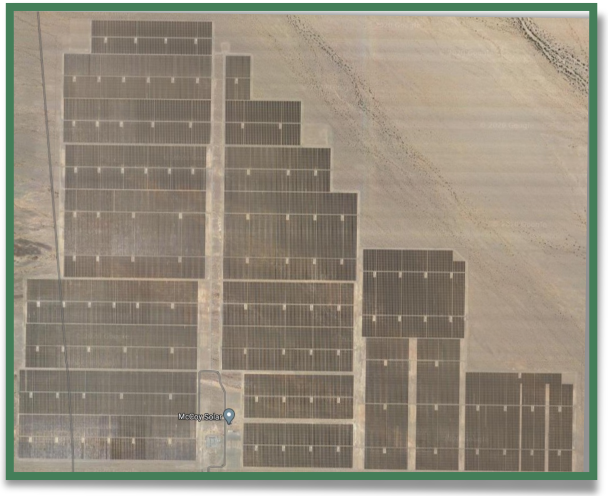
EMT – Electromagnetic Transient
TS – Transient Stability
ac – Alternating Current
dc – Direct Current

Models: 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)



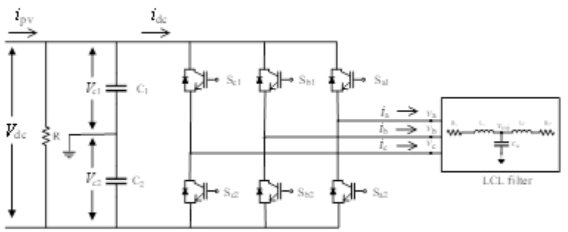
PV Power Plant
(100s of inverters, 10s – 1,000 MW)

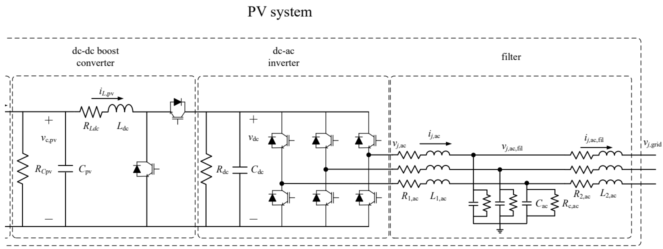
HVdc Substation
(2,400 PE modules, 100 – 3,000 MW)

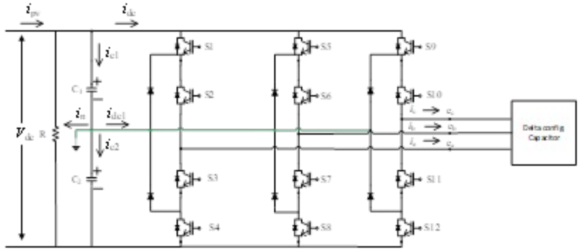
Hybrid Plant (1,500 PE modules, 100 – 2,000 MW)

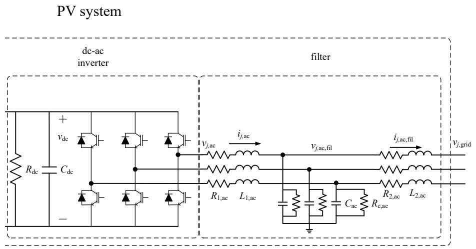
EV Charging Stations (300 chargers in T&D grid)

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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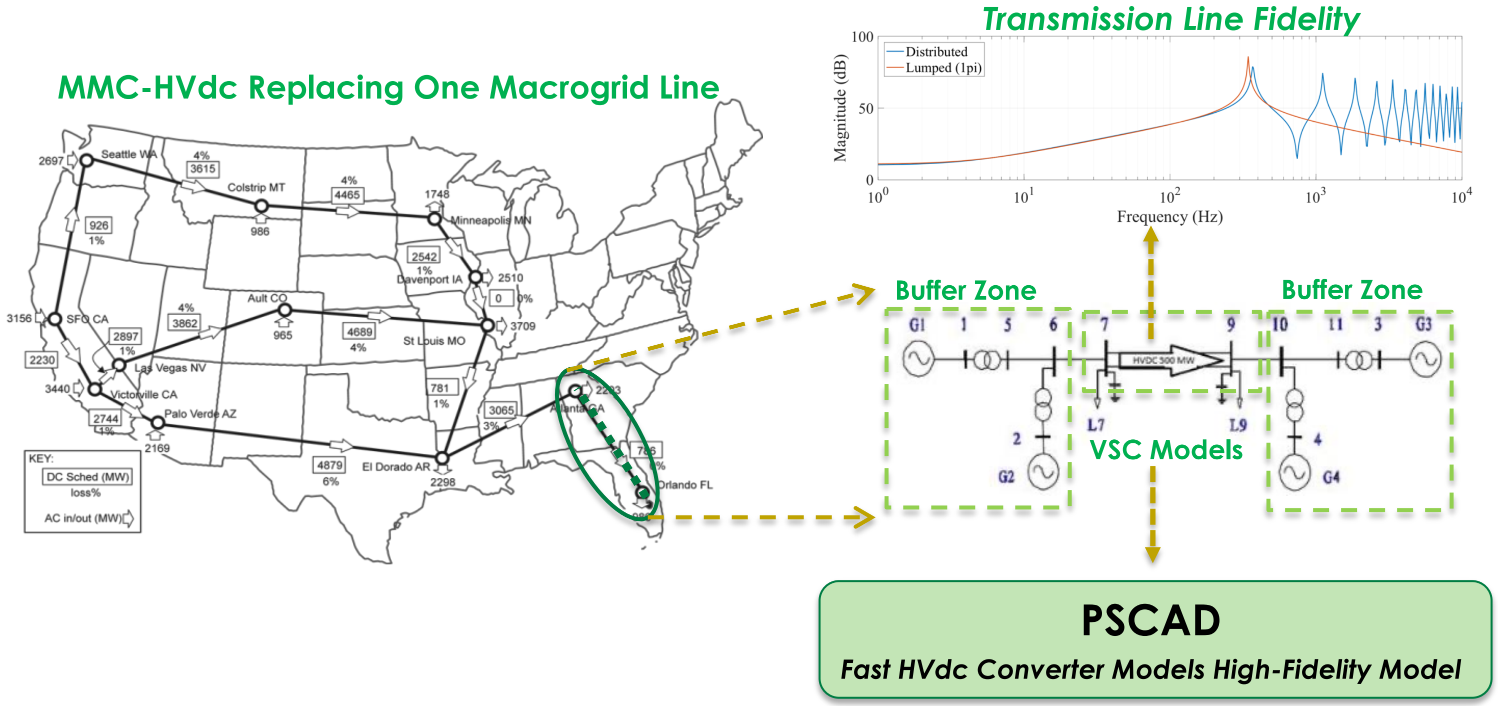
Suman Debnath, Phani Marthi, Jongchan Choi, "Applied Mathematics Challenge: Simulation of Power Electronics in Future Power Grid", SIGSIM-PADS 2022 invited paper

Approach: Fidelity Requirement Analysis



- Use cases analyzed (like dc faults, ac faults)
  - Fidelity of transmission line (frequency-dependent)
  - Fidelity of HVdc stations to support high bandwidth control methods
  - Size of ac grid in EMT needed

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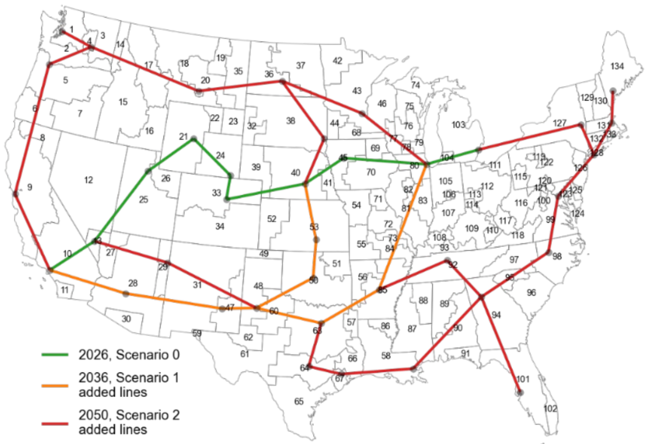
S. Debnath and J. Sun, "Fidelity Requirements with Fast Transients from VSC-HVdc," *IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society*, Washington, DC, USA, 2018, pp. 6007-6014

Approach: EMT Simulation for HVdc Scenario-0

- **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.



***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

Rows 1–4: Lower power ratings

Rows 5–10: Higher power ratings

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

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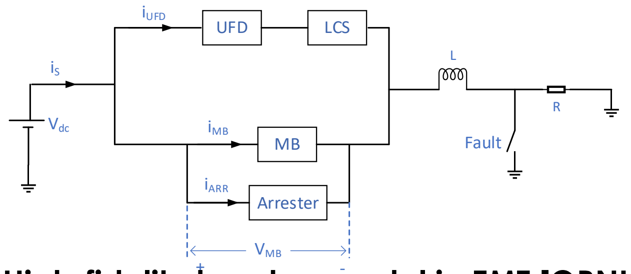
Process & Data: To Set Up EMT Study in Planning

- Individual component model
  - 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.
  - Frequency-dependent transmission line model.
  - Data for sizing of each component and design information is needed



High-fidelity breaker model in EMT [ORNL]

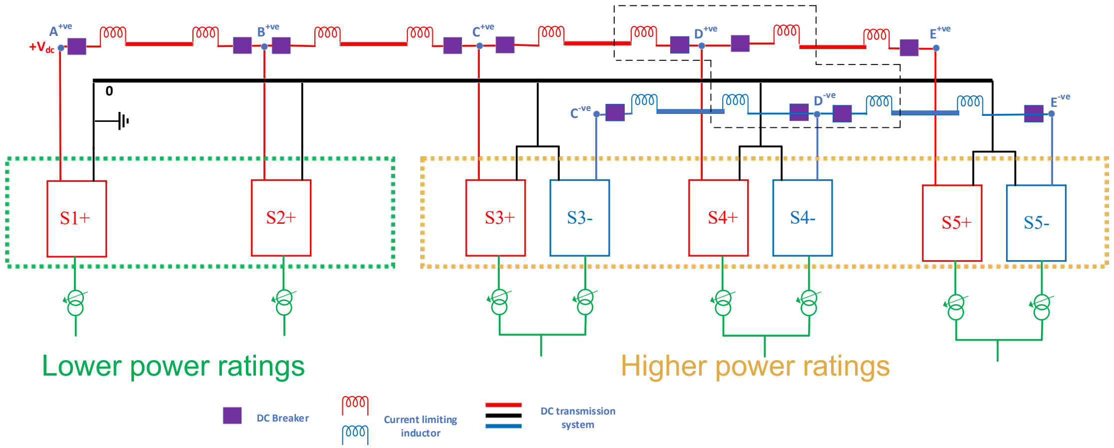
- Grid model
  - Buffer zones extracted from future grid scenarios (TS to EMT conversion) with support from PNNL
  - Data for the year of the model to be used from TS domain needed (with changes in generation)

- **Software Used:** PSCAD, Fortran

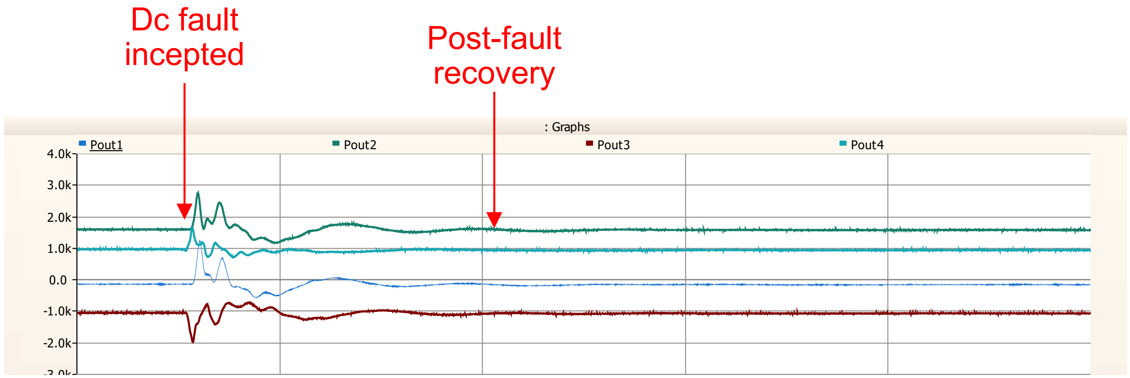
Analysis of HVdc Scenario-0

- **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

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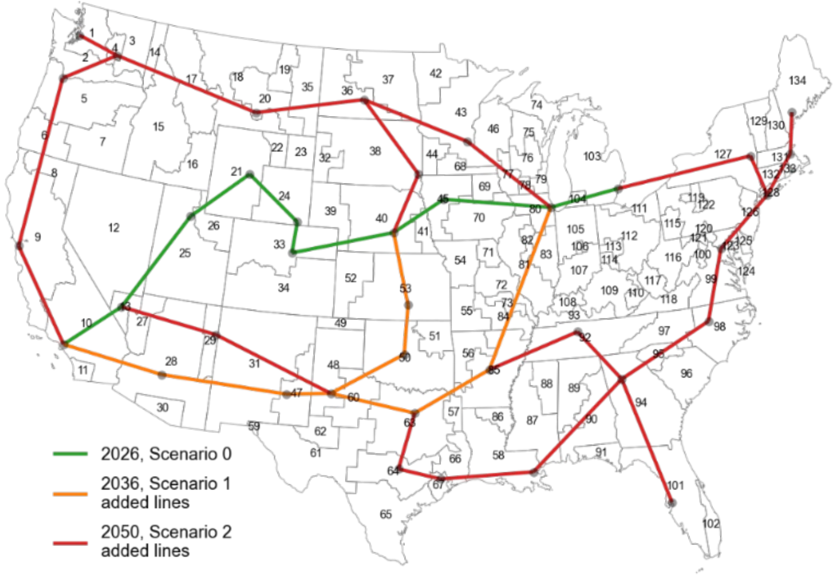
Sreenivasa Sivaprasad Jaldanki, Suman Debnath, Jiazi Zhang, Patrick Brown, Joshua Novacheck, "Mixed Monopole and Bipole MTdc Architecture", accepted in ECCE 2023

Approach: EMT Simulation for Planning Studies

- **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]**

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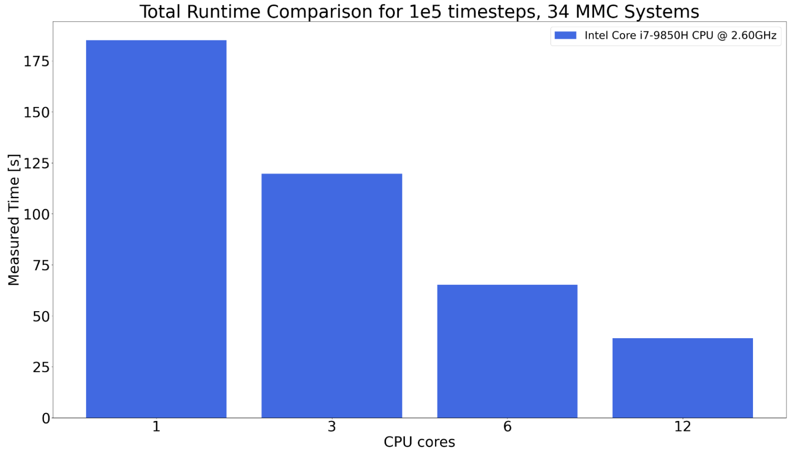
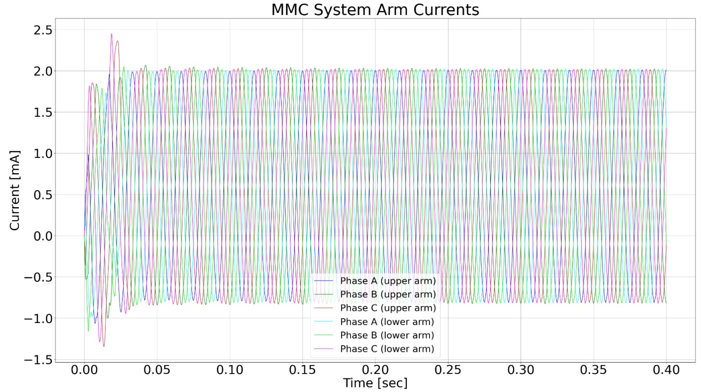
Setup Simulation Results for HVdc Scenario-1

- **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)

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Lessons Learnt (if any)

- EMT-only simulation has been used to design scalable HVdc systems and evaluate their reliability
- EMT simulation with buffer zones have been useful to evaluate faults near the terminals of the HVdc station
- EMT-TS co-simulation has assisted with scalable dc-ac system analysis, where the focus is not on IBR integration

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Impact

- Analysis methods have assisted with scalable system studies
- Helped with understanding the system needs in large-scale dc systems

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Gaps & Challenges Observed (Not Solved Yet)

- Large-scale dc penetration yet to be analyzed (e.g., 50 nodes or higher)
- Increased penetration of IBRs require HVdc-IBR studies at a large-scale
- Scalability yet to be evaluated for a large number of nodes (~1,000s) for EMT-TS hybrid simulations

Acknowledgements

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Pacific Northwest
NATIONAL LABORATORY

Hybrid Simulations for Electromagnetic Transients and Phasor Dynamic Models

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March 1, 2023

U.S. DEPARTMENT OF ENERGY BATTELLE

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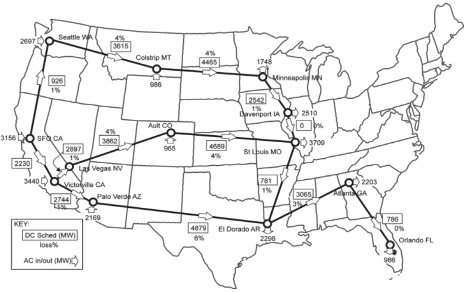
Dynamic Modeling Landscape

TS (phasor models)

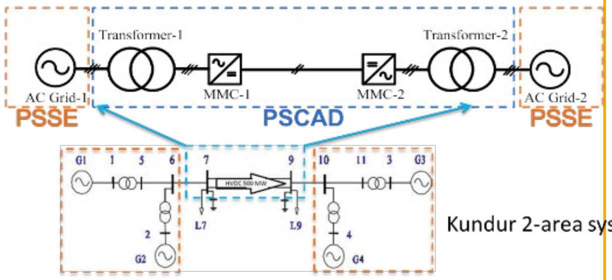


Electromechanical phenomenon

- Transient stability studies
- Governor control
  (frequency response)
- Transmission planning studies
- Simplified HVDC converters

Less detail – large area

Hybrid Simulation

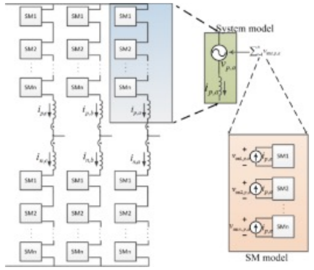


Kundur 2-area system

Lumped models

Middle ground

EMT



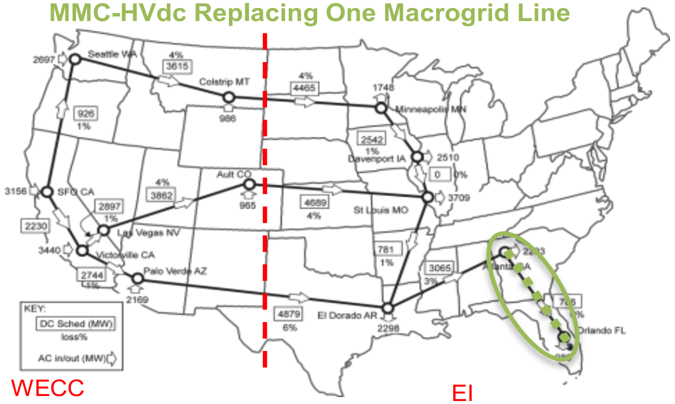
Electromagnetic phenomenon

- Switching surges
- Sub-synchronous resonance
- Detailed HVDC converters

More detail – small area

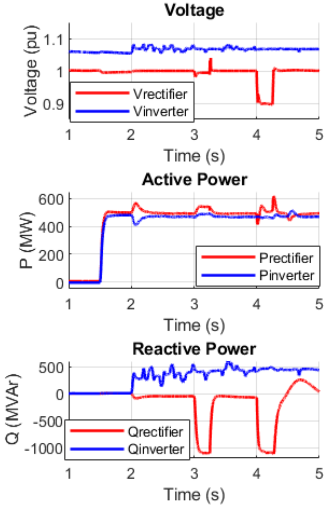
Computational Performance Hybrid EMT-TS Simulation: EI + 1 line MMC

MMC-HVdc Replacing One Macrogrid Line

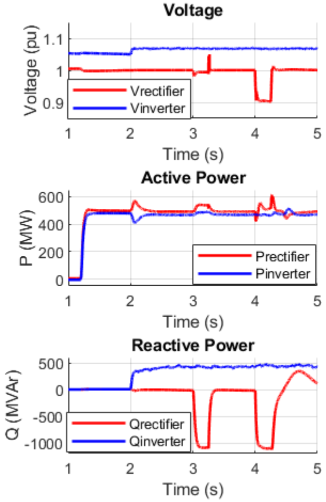


WECC
(equivalent power injection at HVdc terminals)

EI
(full dynamic model)



Large buffer zone + Fast MMC model



Small buffer zone + Fast MMC model

Table: Computation performance for 5-second simulation length

Buffer zone size		Type of simulation	EMT time step - ORNL's HVdc system model	TS time step	Simulation time	Speedup
Smaller	17 buses, 8 boundary buses	EMT-TS co-simulation	60 µs – Fast	4.16 ms	287 s	2.4x
			4 µs – Slow	4.16 ms	706 s	
larger	62 buses, 25 boundary buses	EMT-TS co-simulation	60 us – Fast	4.16 ms	391 s	3.4x
			4 us – Slow	4.16 ms	1,351	

Computer Configuration:

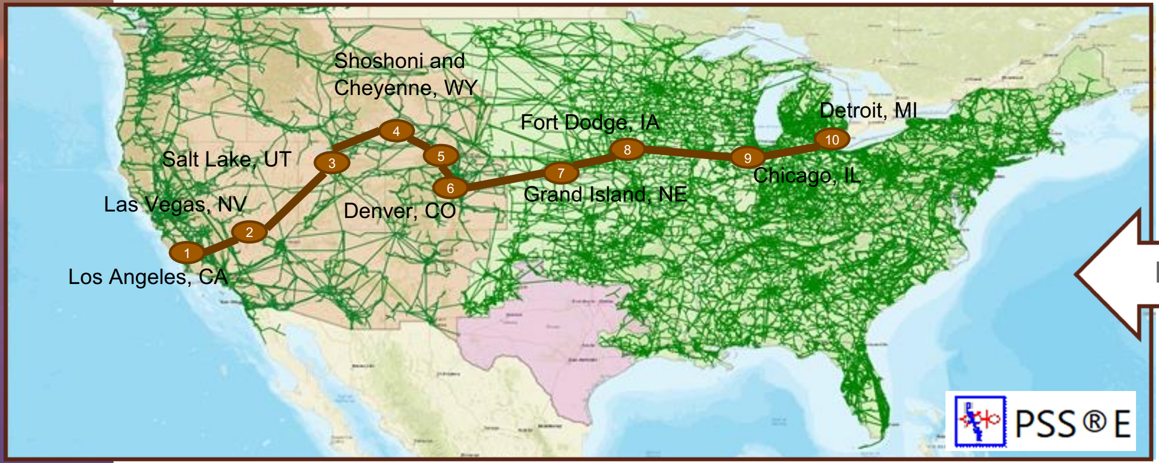
Processor:	Intel(R) Core(TM) i7-6820HQ CPU @ 2.70GHz 2.70 GHz
Installed memory (RAM):	16.0 GB (15.7 GB usable)
System type:	64-bit Operating System, x64-based processor

PSCAD Version: 4.6.2, PSS/E Version: 33.7

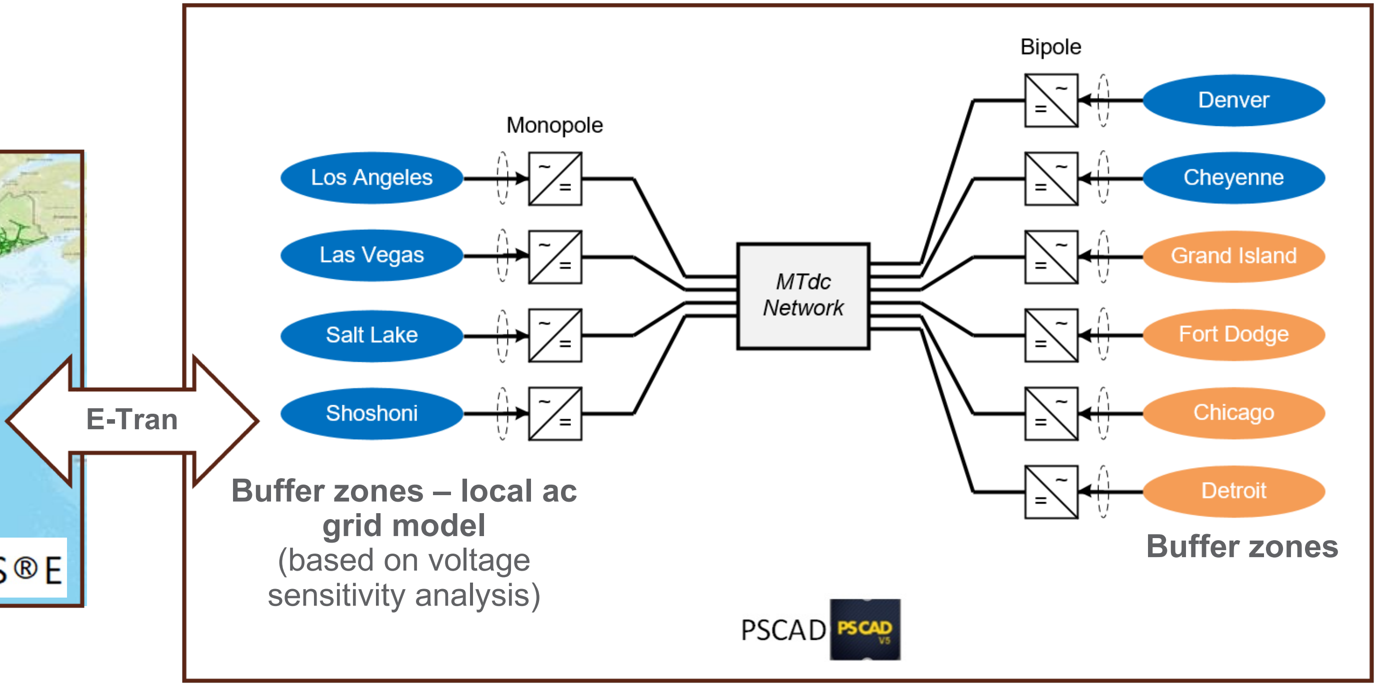
Liu et al, "Hybrid EMT-TS Simulation Strategies to Study High Bandwidth MMC-Based HVdc Systems" IEEE PES GM, Aug. 2020
Suman Debnath, Marcelo Elizondo, et. al., "Models And Methods For Assessing The Value Of Hvdc And Mvdc Technologies In Modern Power Grids", GMLC Report, Sept 2019

Compromise Between High-Fidelity and Computation Effort

- 10-station MTdc Network in EMT and Full 100,000-buses WI and EI Interconnections in TS
  - Analyzed for reliability in EMT-TS hybrid model for ac grid faults
  - 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]
  - PSCAD, PSSE, E-Tran



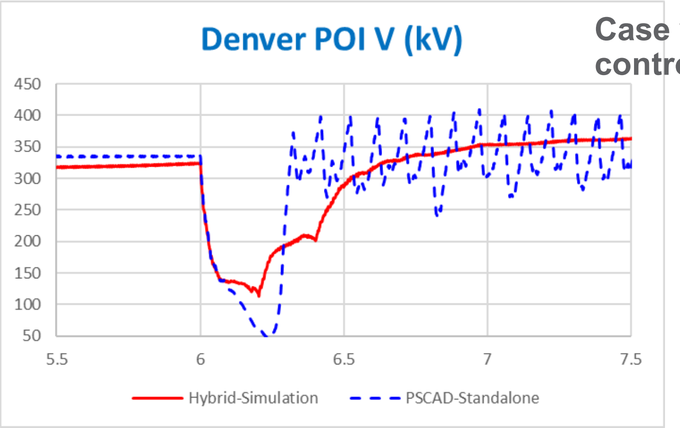
***Scenario*: 10-terminal radial MTdc scenario planned with point of interconnection in the ac grid**



Project funded by DOE OE TRAC; POCs for this task: Marcelo Elizondo (PNNL) and Suman Debnath (ORNL)

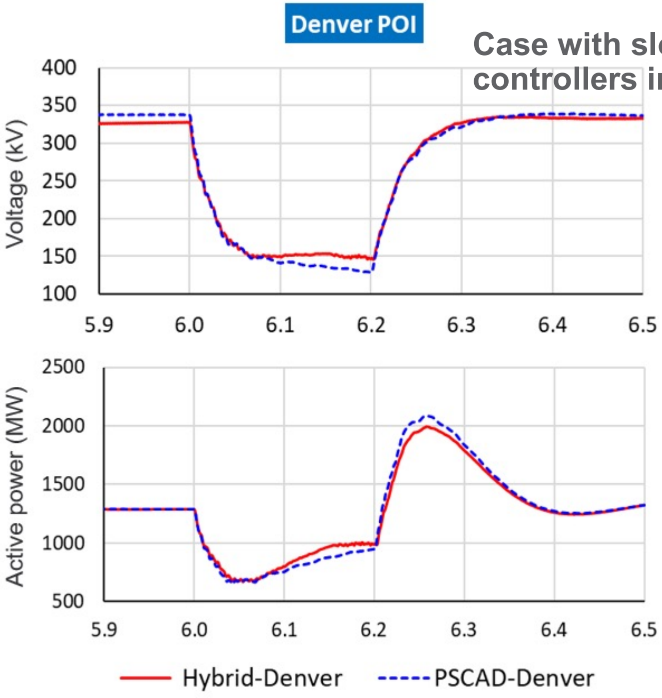
Compromise Between High-Fidelity and Computation Effort

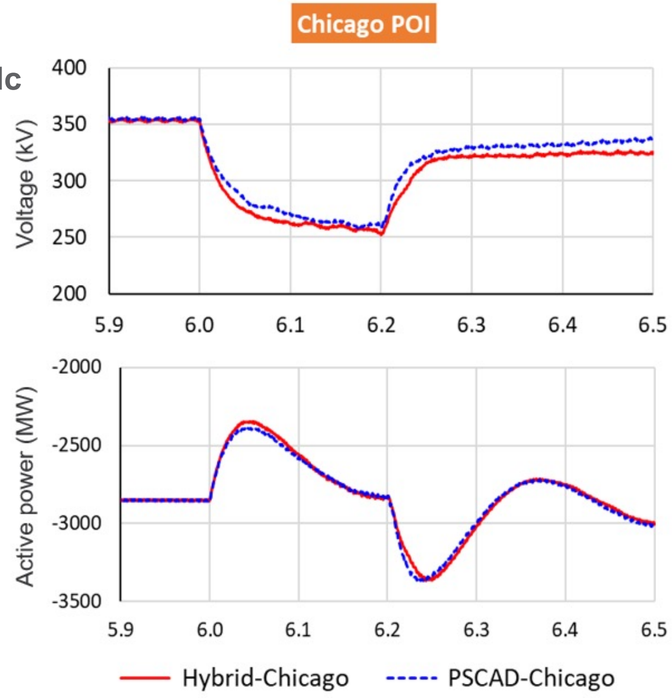
- Large scale EMT-TS Co-Simulation: 10-Station MTdc (EMT) in EI-WECC 100,000 bus dynamic model (TS)
  - Tested ac faults in different locations in WI and EI sides
  - Good compatibility between full EMT and co-simulation is observed once controllers are slowed down
  - Opportunity for improved simulation algorithms and HPC techniques for scalability



Case with faster controllers in MTdc

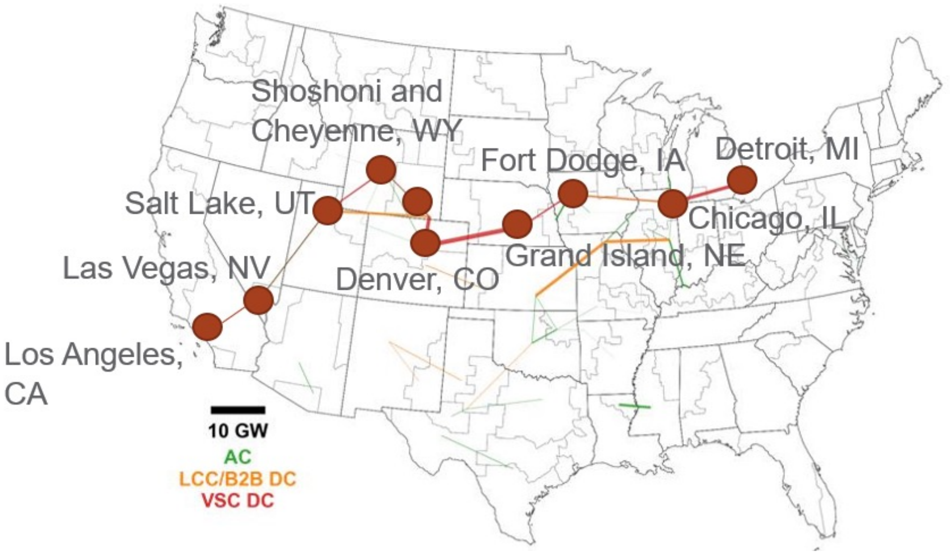
Case with slower controllers in MTdc



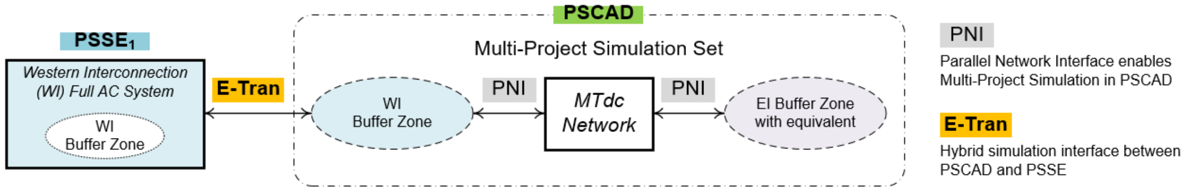


Computational Performance Hybrid EMT-TS Simulation: WECC-EI + 10-station MTDC

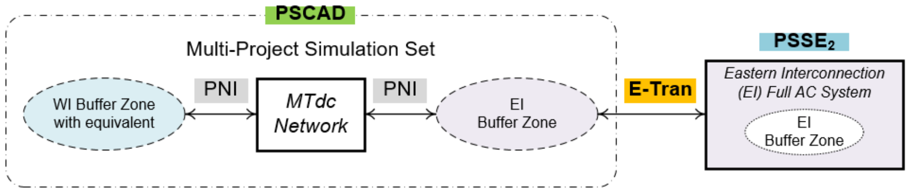
Simulation Case	Simulation Machine Specification	Number of Boundary Buses	1) PSCAD time step 2) PSSE time step	Simulation time	Total CPU time	Average CPU time
Set up1	Processor: AMD Opeteron Processor 6272, 2.10 GHz (2 processors) RAM: 64 GB	83 (WI)	1) 4.000 us 2) 1.000 ms (EI), 3.333 ms (WI)	6 s	18,841 s	52.33 min/s
Set up2		53 (EI)			17,841 s	49.56 min/s
Set up3		136 (WI + EI)			20,275 s	56.32 min/s



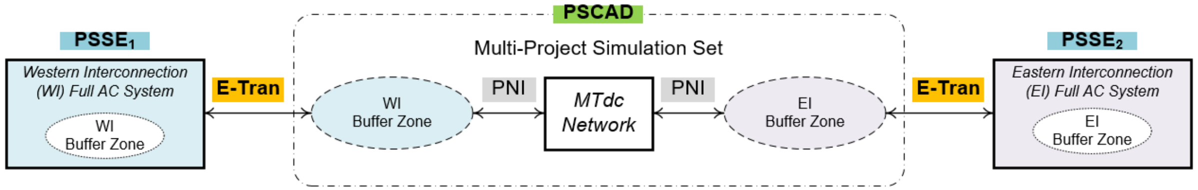
Hybrid EMT-TS Simulation Set up1



Hybrid EMT-TS Simulation Set up2

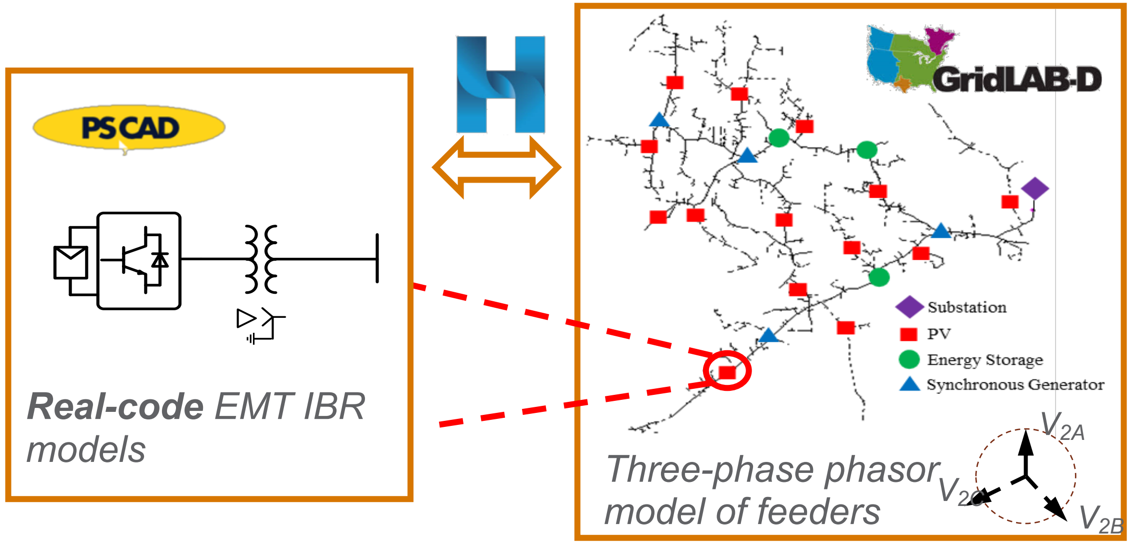


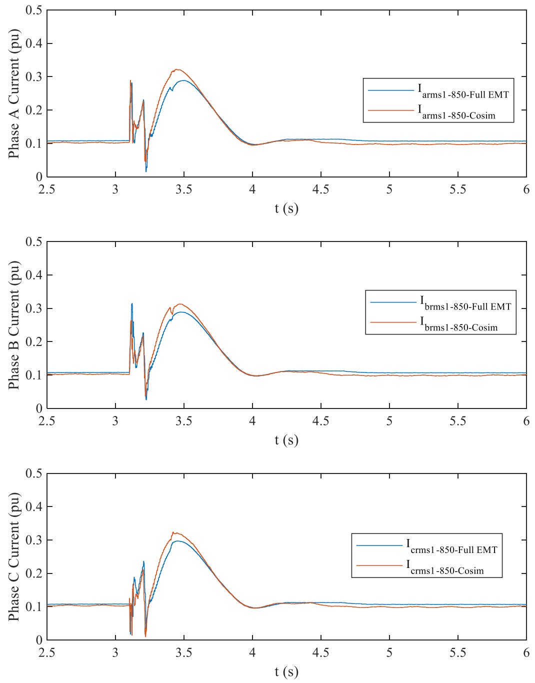
Hybrid EMT-TS Simulation Set up3



EMT & Individual Phasor Co-Simulation Platform

- ***EMT and Individual Phase Phasor Co-Simulation***
  - Expand HELICS to interconnect PSCAD and GridLAB-D to realize EMT & phasor co-simulation for distribution systems
  - Allow ***real-code*** PSCAD EMT models of IBRs to be directly connected to utilities' full-size feeder models





Computational Time (runtime:

Model	Time Step	Execution Time
Full-EMT	10 *μs*	314.67 s
Co-simulation	10 *μs* / 2 *ms* / 4 *ms*	179.72 s

This project is funded by the SETO Lab Call FY22-24 project "Integrated Multi-Fidelity Model and Co-Simulation Platform for Distribution System Transient and Dynamic Analysis—DistribuDyn" (POC: Wei Du)

Summary

- Large scale EMT simulations challenged by high computational requirements
- TS (phasor dynamic models) have been historically used for modeling large scale interconnections, such as EI and WECC
- Hybrid EMT-TS simulations can achieve compromise between computational effort and model accuracy
  - Scalability to 10-Station MTdc (EMT) in EI-WECC 100,000 bus dynamic model (TS), but still with high computational effort required
- Other EMT-TS activities ongoing
  - EMT and 3-phase TS hybrid simulation at distribution feeders/microgrid
  - GridPACK for Wind Integration and system-level EMT speedup investigation (DOE-OE AGM + DOE-EERE WETO, POC: Shri Abhyankar, PNNL)
  - Modeling gaps for high penetration of IBRs (DOE OE AGM, POC: Nader Samaan, PNNL)
- When to use EMT, TS, and EMT-TS hybrid remain an open question and guidance for modelers is needed

Thank you

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