U.S. DEPARTMENT OF ENERGY
Office of Electricity

# Project-1: HVdc Models & Methods

# Project-2: Gap Analysis

**TRAC Program Review**

*US Department of Energy, Office of Electricity*

**Presented at Oak Ridge National Laboratory**

*Oak Ridge, TN*

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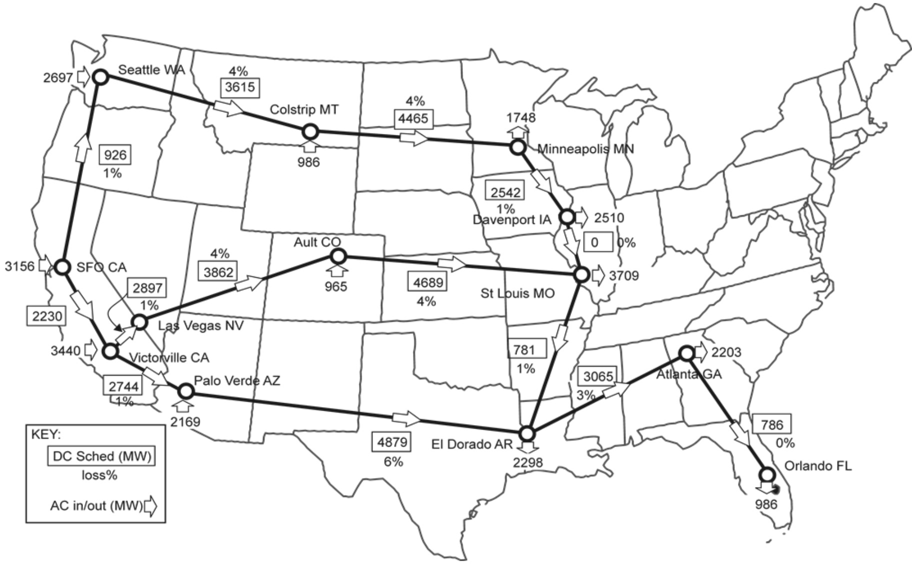
# HVdc Models & Methods: Project Overview

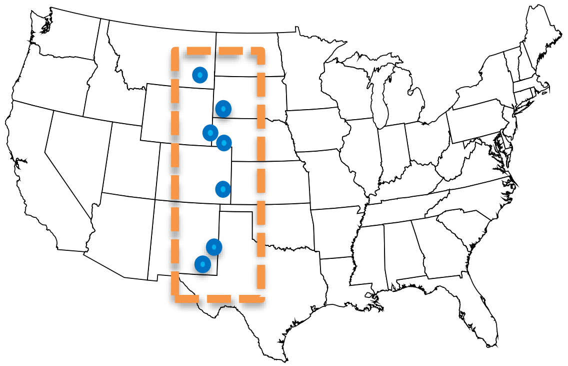
- *Objective*
  - Develop the models and methods for assessing the impact of dc technologies to improve reliability and economics of grid
- *Approach*
  - High-fidelity power electronic switched system model in PSCAD (electro-magnetic transients [EMT])
  - Hybrid simulation of PSCAD-PSS®E (EMT and transient stability [TS] dynamics) through E-TRAN
  - PSS®E-PLEXOS interaction through PIDG to identify economic benefits
- *Total award, period of performance*: $1.3M, 2017-19
- *Project team*: ORNL (Lead), PNNL, NREL



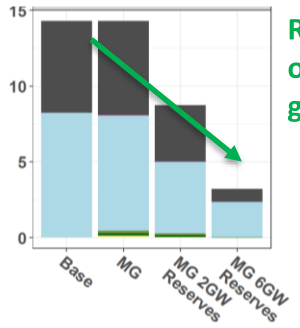

Example dc system architecture ~ 14 GW transfer capability

# Context

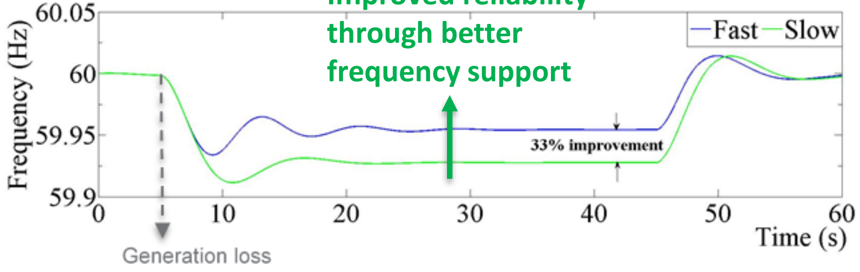
- Gaps in quantifying techno-economic benefits associated with fast control methods in power electronics
- Increased costs associated with maintaining reserves
- Aging grid infrastructure (and dc links connecting interconnections)
- *Impact*
  - Improved economics
  - Increased reliability



Existing dc links connecting eastern interconnection (EI), western interconnection (WI) ~ 1.0 GW transfer capability




Reduced costs of operating grids



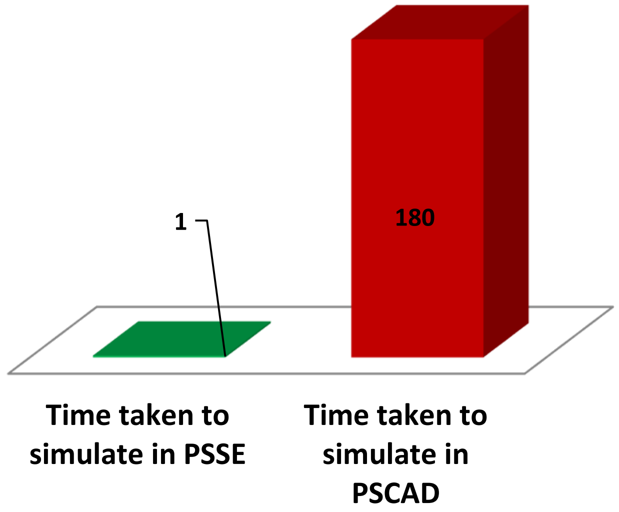

Improved reliability through better frequency support

# State of the Art

- *Limitations in existing high voltage direct current (HVdc) topology studies*
  - Limited quantification of dynamic response provided by HVdc topologies
  - Limited comparisons between different HVdc topologies with dynamics support
- *Limitations in existing tools to study dc-ac systems*
  - Slower high-fidelity EMT models of HVdc substations
  - Minimum hybrid EMT-TS analysis performed to evaluate impact of high bandwidth control on power electronics
  - Limited economic analysis from technical benefits quantified through fast control methods in HVdc substations

AEMO has combined the PSCAD models of individual generators and the SA transmission network to create an integrated PSCAD model of the SA system. This is currently one of the largest PSCAD models of any power system in the world and requires up to 3 hours to simulate 20 seconds on a powerful computer. AEMO has

Courtesy: PSC, "Review of AEMO's PSCAD Modelling of the Power System in South Australia"






Advanced Grid Research
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# Uniqueness

- *Simulation Algorithm & Modeling:* Advanced mathematics (numerical stiffness and temporal parallelism) based separation and reduction in matrix reduction requirements in EMT simulations
- *Hybrid Simulation & Model Conversion Methods:* Quantification of fidelity requirements and methods to co-simulate EMT-TS simulation; utilization of model (TS to EMT) conversion methods
- *Multi-Objective Control Methods:* Multi-objective control methods for improved frequency response control that is provided by HVdc systems
- *Advanced Control Methods & Comparison of Scenarios:* Simultaneous congestion mitigation and frequency response support provided by HVdc systems and comparison of different dc penetrations
- *Economic Quantification:* Quantification of economics associated with high bandwidth control methods

**PSCAD**
**High-fidelity power electronic and component models, and buffer zone models to develop high bandwidth advanced control methods**

↔

**PSSE**
**ac system dynamic models to quantify frequency and congestion benefits provided by HVdc systems**

→

**PLEXOS**
**Economic benefits quantification from cost models, frequency & congestion management benefits assessed**

Oak Ridge National Laboratory

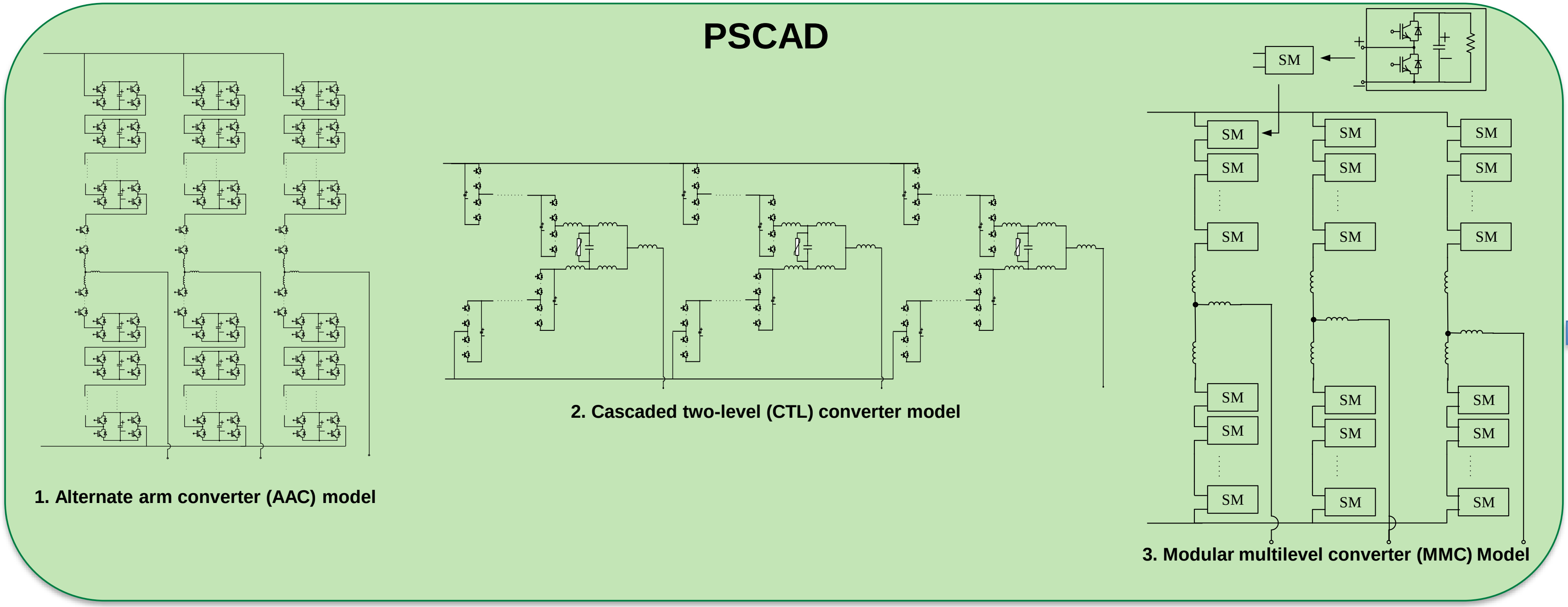
Pacific Northwest National Laboratory

NREL National Renewable Energy Laboratory

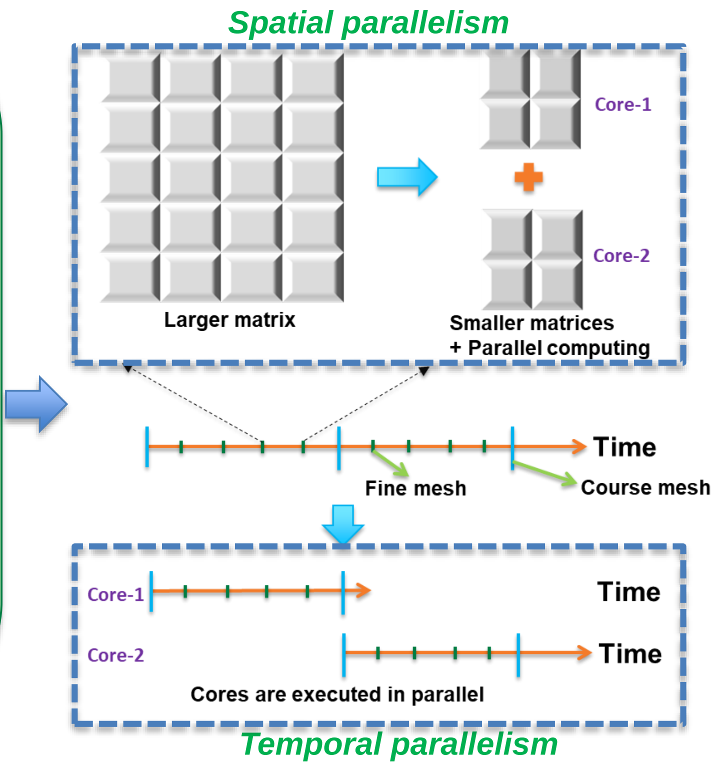
# Research Questions

- How can high-fidelity EMT simulations be performed in reasonable time-frame (~ similar time-frame as TS simulations)?
- How can EMT-TS cosimulations be performed and what are the fidelity models required?
- What are the benefits of fast control methods?
- How can fast control methods in power electronics be quantified in terms of economics?
- What are the HVdc topologies of interest in connecting interconnections?

# Technical Approach & Outcome: Models & Simulation Algorithms




*Fast Multi-level Voltage Source Converter (VSC) HVdc Converter Models*



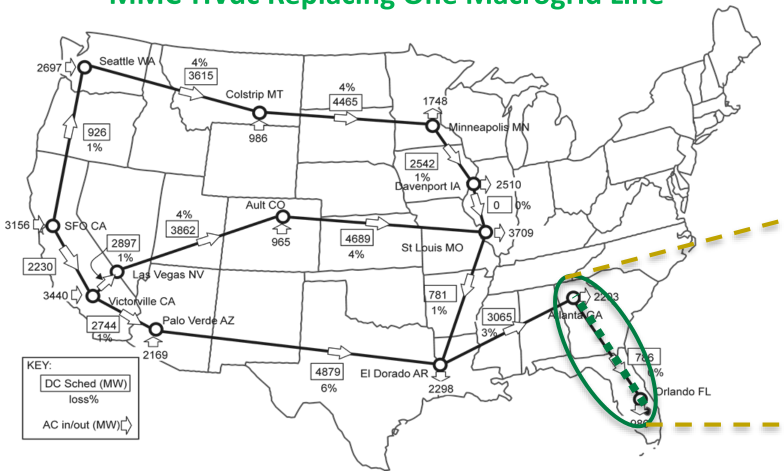

## *Highlights of Simulation Algorithms & High-Fidelity Models*

- Up to 12x speed-up using **spatial parallelism** based on numerical stiffness
- 3 complex multi-level converter models (namely AAC, CTL, MMC VSCs) developed
- Can be extended to **other complex power electronic systems** like wind, solar, variable-frequency drives, microgrids, multi-port power electronics, transmission-distribution systems, and others
- **Temporal parallelization** with N times speed-up (N: No. of cores)

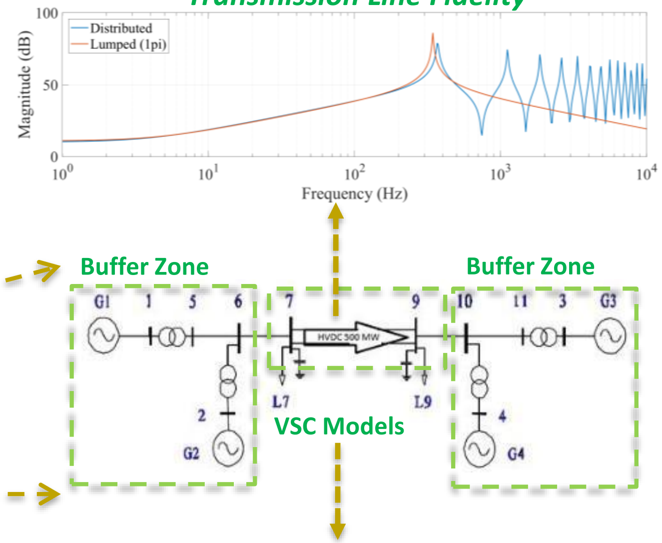
**Request for models to be sent to debnaths@ornl.gov**

# Technical Approach & Outcome: Hybrid Simulation Methods

**MMC-HVdc Replacing One Macrogrid Line**




**Transmission Line Fidelity**

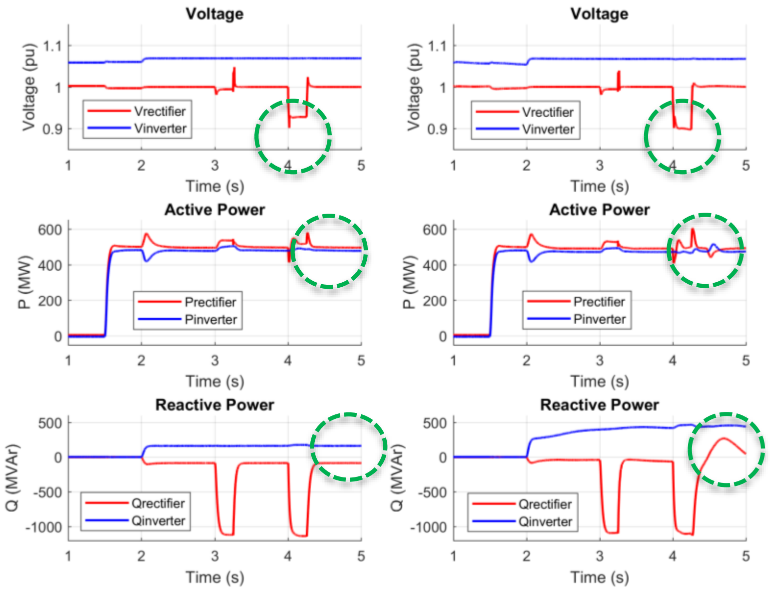



**PSS®E**
**ac grid models (EI, WECC)**

**E-TRAN**

**PSCAD**
***Fast HVdc Converter Models High-Fidelity Model***

**PSCAD Buffer Zone Model** | **Hybrid Simulation Model**



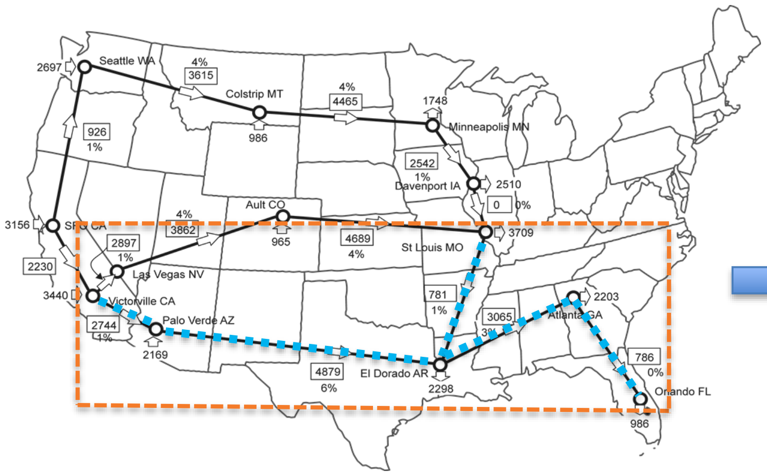

## *Highlights of EMT-TS Hybrid Simulation Methods*

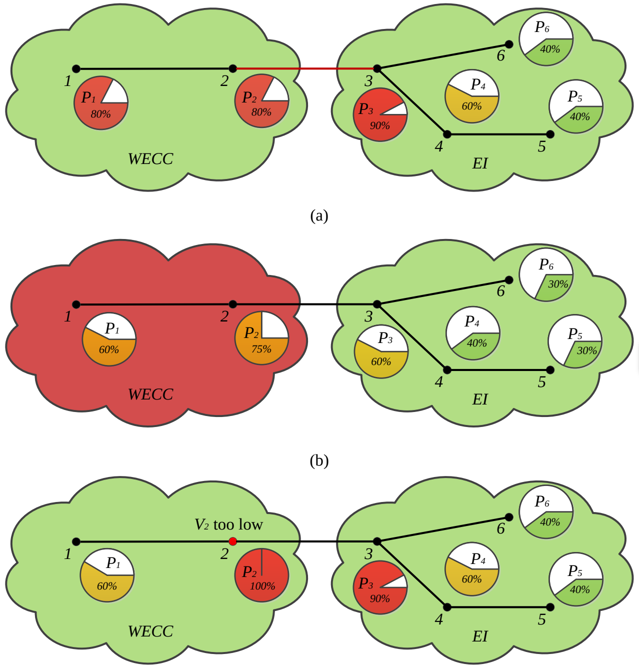
- Quantified fidelity of power electronics (PE) and transmission lines
- Identified buffer zone requirements for hybrid simulation – need increases with faster control methods in power electronics
- Supports associated PE high bandwidth control methods
- Speed-up observed up to 6x observed with multi-rate methods

**Request for models/methods to be sent to debnaths@ornl.gov**

# Technical Approach & Outcome: Multi-Objective Optimal Control Methods

MTdc network connecting asynchronous grids

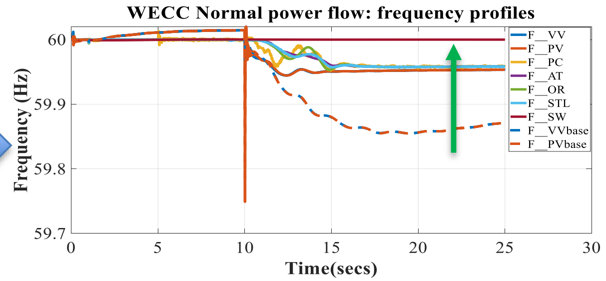



(a) (b) (c)

Multi-objective optimal control method to provide fast frequency response

Improved frequency response




**PSCAD**

*Fast HVdc Converter Models*

E-TRAN

**PSS®E**

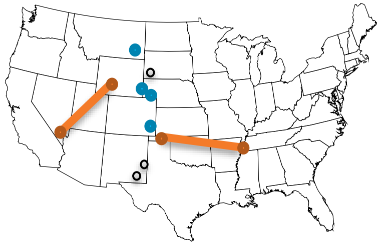
(Lumped Models Translated to PSCAD)

### *Highlights of Multi-Objective Optimal Control Methods & Model Conversion Methods*

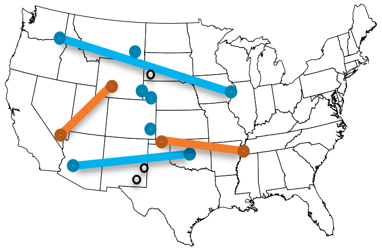
- Multi-terminal dc (MTdc) **multi-objective optimal control methods** that improve frequency response by up 66% while connecting EI, ERCOT, and WECC through fast frequency response support. Better annual economic benefits as shown in next slide
- Up to 33% improvement compared to slower frequency response support that could utilize slower models
- Up to **7-terminal MTdc network** models developed (available in PSCAD)
- Faster **lumped ac grid models** of EI and WI that represent frequency behavior
- PSCAD to PSS®E conversion method applied and limitations quantified

**Request for models to be sent to debnaths@ornl.gov**

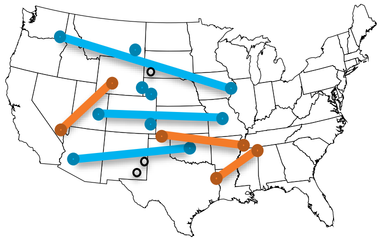
# Technical Approach & Outcome: Comparison of Scenarios & Economics



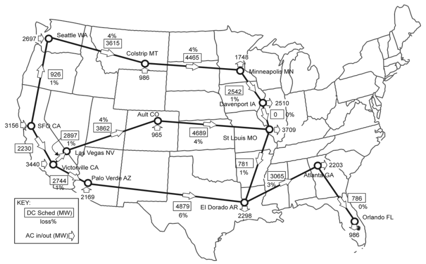
Topology 1 (Scenario 2a & Industry lines)



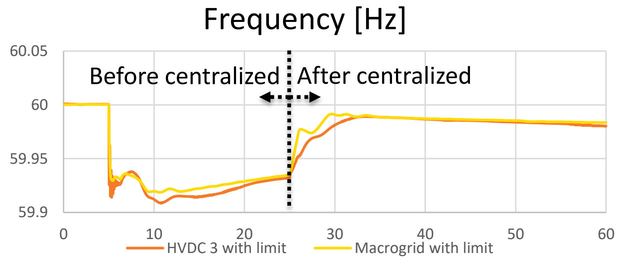
Topology 2 (Scenario 2b & Industry lines)



Topology 3 (Scenario 2b & Industry lines)



Topology 4 (Scenario 3)

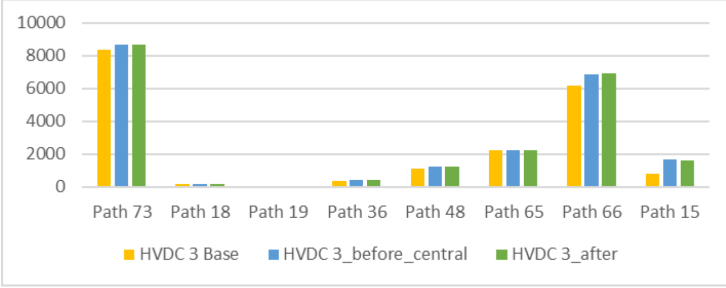


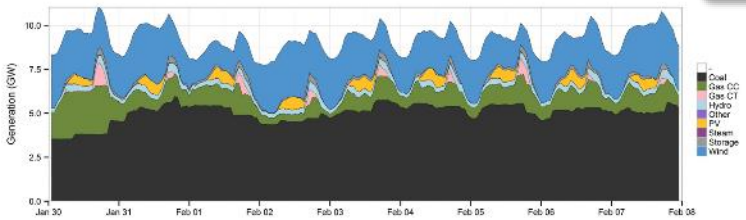

***Congestion & Dynamic Benefits (frequency)***

**PSS®E**

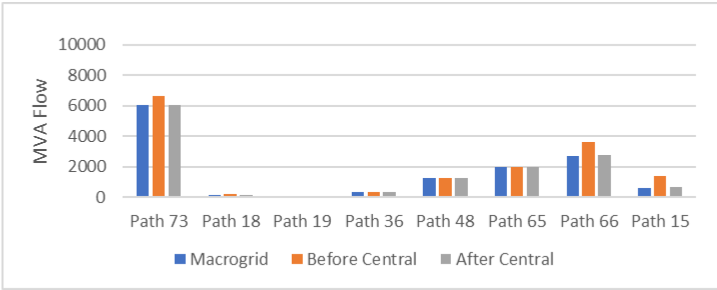
Translation tool for model conversion **PIDG**

**PLEXOS**




***Economic benefits ($)***




## *Highlights of Comparison of Scenarios & Advanced Control Methods, Economic Quantification*

- dc penetration scenarios compared with macrogrid providing better congestion benefits
- PIDG 2.0 that interacts between PSS®E and PLEXOS has been speed-up of 10x and can now utilize up to 100,000 bus models (compared to 6,000 previously)
- Annual benefits of $241 million vs $105 million when comparing greater frequency reserve reduction that is possible with faster frequency response and optimal control in MTdc systems

# Broader Impact

- Impact of models & methods
  - **Models being used by 2 Universities**
  - **Discussions with Industry partners on sharing the VSC and MTdc models**
  - **Gaps identified in EMT and EMT-TS simulations as also in TS to EMT conversion methods**
  - **Improvements suggested to Electranix (E-TRAN developer) for improvement of hybrid simulation methods**
  - **Three conference and two journal papers accepted**
  - **Two conference and two journal papers in press/submitted**
  - **Developed models and methods for faster EMT and EMT-TS simulations are applicable to other power electronics technologies (wind, PV, variable-speed drives) and scenarios like NERC IRPTF**
  - **Successful collaboration between ORNL, PNNL, NREL to utilize strengths at each lab**
- Challenges faced
  - Identifying stable modes of parallelization in power electronic simulations
  - Stability of conversion from PSS®E to PSCAD
  - Hybrid simulation with large number of nodes in PSCAD
  - PIDG model conversion with large number of buses
  - Slow nature of EMT simulations and EMT-TS hybrid simulations

NERC – North American Electric Reliability Corporation
IRPTF – Inverter-based Resource Performance Task Force

# Lessons Learned

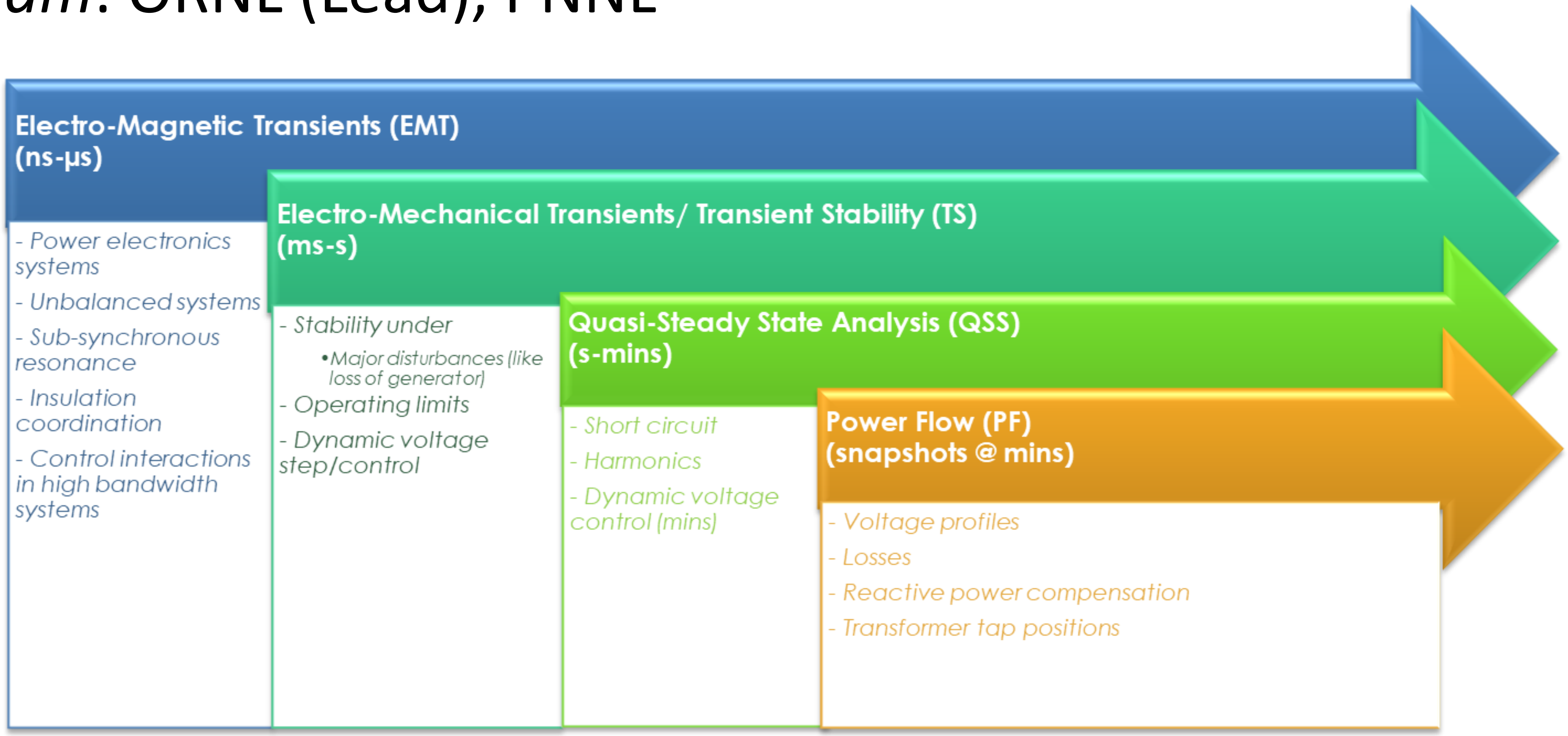
- High-fidelity power electronic models required in analysis of large-scale HVdc-ac system with advanced control methods
- Spatial and temporal parallelization is stable with large power electronic systems to speed-up simulation
- Large-scale MTdc systems can provide fast decentralized control (inertial, primary response) at multiple points of injection to overcome rating limitations
- Hybrid simulation between PSS®E and PSCAD requires further analysis with larger HVdc systems to identify scalability problems (if any) – discussions with Electranix Corporations
- Larger penetration of HVdc systems provide improved congestion benefits while providing frequency support or otherwise
- There are gaps identified in EMT simulation of dc-ac systems with respect to speed
- There are gaps identified in EMT-TS cosimulations and TS to EMT simulation conversions

# Future Studies

- Gaps identified in this project are being explored more in-depth for future power electronic scenarios
- Further analysis required to understand MTdc scenarios with greater penetration (eg, macrogrid) including protection and control requirements
- Simulation algorithms (spatial-temporal methods) scalability to large-scale dc-ac systems, power electronics systems, and others
- Hybrid simulation algorithms development requirements for large-scale studies – identify boundaries of TS and EMT simulation – an important enabler for future studies
- Metrics to quantify requirements of EMT or EMT-TS simulations
- Reduced frequency reserves and voltage control methods require better understanding to identify the indirect costs benefits (economics)

# Gap Analysis: Project Overview

- *Objective*
  - Identify gaps in existing simulation tools for futuristic scenarios of high penetration power electronics
- *Total award, period of performance*: $240K, 2019-20
- *Project team*: ORNL (Lead), PNNL



# Context

- Gaps have been identified in the dc-ac system project to simulate large-scale dc systems
- Increasing EMT study requirements necessitated by utilities/ISOs (eg, AEMO, ERCOT, NE-ISO) and the corresponding constraints
  - AEMO study for South Australian grid took 3 hours for 20 s — Courtesy: PSC, "Review of AEMO's PSCAD Modelling of the Power System in South Australia"
  - ERCOT study for Pan Handle region took up to 2 hours for 30 s — Courtesy: Electranix, "Panhandle and South Texas Stability and System Strength Assessment"
  - TS simulation of a much larger region (WI) takes 12 minutes
- Further penetration of power electronics through solid-state power substations
- *Impact*
  - Inform decision makers about future research requirements and directions
  - Enabler for large-scale power electronics penetration in grids including transportation, energy storage, renewables (wind, photovoltaic), variable-frequency drives, and others

ISO – Independent System Operator
AEMO – Australian Energy Market Operator
ERCOT – Electric Reliability Council of Texas
NE-ISO – New England ISO

# State-of-the-Art Studies

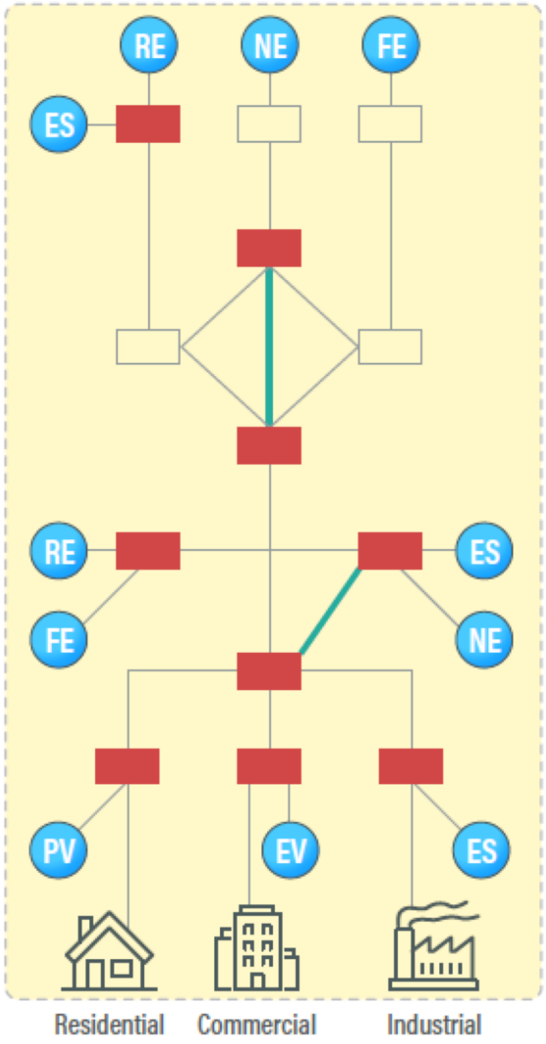
- Existing literature has limited information on future grid requirements with high penetration of various types of power electronics
- Recent PES-GM meetings and NERC IRPTF have identified study requirements utilizing higher fidelity models for increased penetration of power electronics
- Previous studies have considered high-penetration photovoltaics or high-penetration of wind – there are still multiple gaps in such studies that need identification of future directions of research

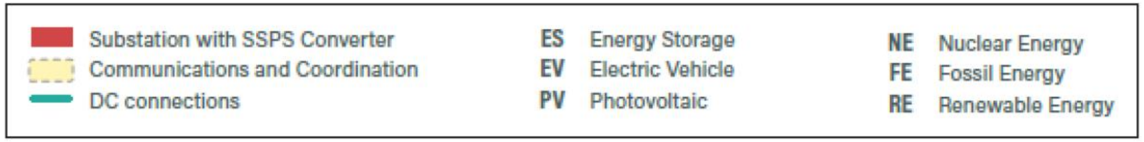
Software tools are being developed to keep up with the rapidly increasing size and volume of EMT studies being requested. Protection studies using EMT modeling and simulation tools is becoming more common. Concerns about specific relay applications or breaker duties are realizing that conventional fault study tools may be inadequate near inverter-based resource and need confirmation using EMT tools. This is not standardized for every interconnection or relay study, but it is becoming more common.

NERC IRPTF, "Key Takeaways: Inverter Manufacturer and Relay Manufacturer Coordination Meeting", April 2019.

# Significance & Broader Impact & Research Questions

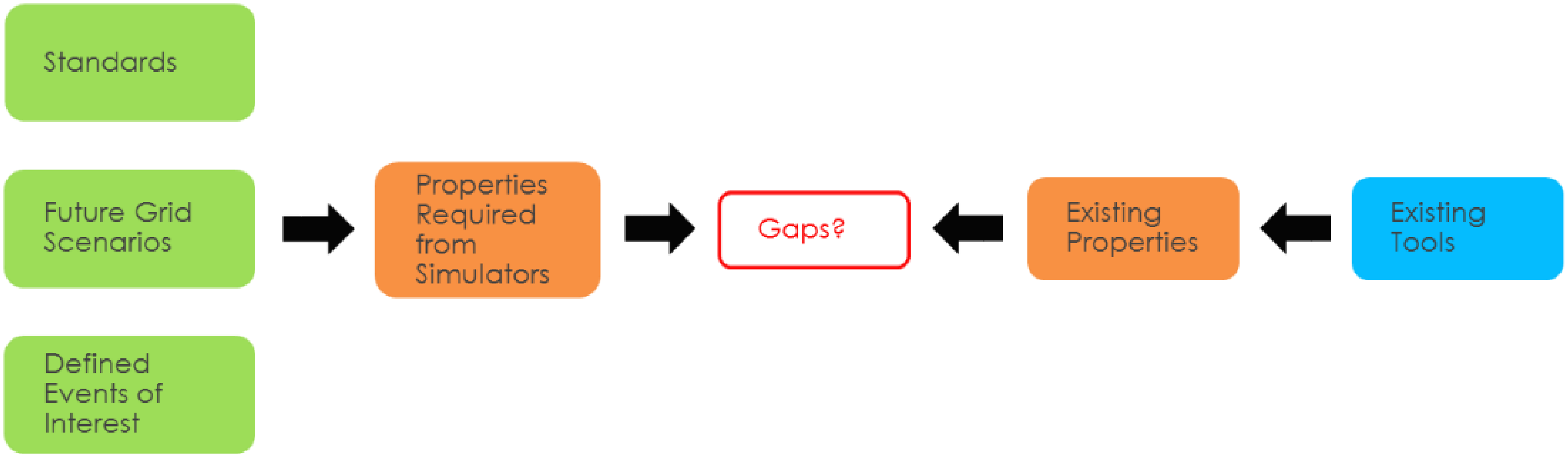
- Success of the project will lead to
  - Mapping research directions for futuristic grid scenarios
  - Enabler for decision making
- Results identified will enable
  - Decision-makers and investors to make better-informed decisions on investments in future tools' research
  - Grid modernization with high penetration of power electronics in future
  - Advanced technology development and demonstration



# Technical Approach: Overview

- Identify future research questions and properties of systems – sample presented
- Identify properties required from simulators
- Properties of existing tools mapped
- Identify gaps based on graph theory



# Technical Approach: Properties of Systems & Metrics

| Characteristics | Traditional Power System | Future Scenario: High-Penetration Power Electronics |
| --- | --- | --- |
| **Interconnections** | Heavily interconnected system | Asynchronous, decoupled, firewalled, fractal sections |
| **Power Dispatch** | Hourly dispatch, with real-time market corrections every 15 and 5 mins (and in 1 min under extreme circumstances – eg, CAISO)<br>[PF studies performed at snapshots] | Faster dispatch feasible with high-penetration of power electronics (~ s or faster) |
| **Dynamics** | *In mins:* Tap changers, mechanically switched capacitors, settings in automatic voltage regulator (AVR)<br>[QSS analysis performed] | *In seconds:* Fast changing power flows due to variability (eg, wind, PV) |
| | *In seconds:* Reactive power flows, voltage controllers, synchronous generators<br>[TS analysis performed] | *In microseconds/ milliseconds:* Dynamics of power electronics |
| **Study Footprints** | Large system studies performed for PF and TS analysis | Smaller system studies may suffice for decoupled systems? |
| | Small systems studied in EMT like in substations design, insulation studies, sub-synchronous oscillations | Larger footprint of EMT studies (than today's studies) to understand stability and system impact? |
| **Load Models** | Aggregated for transmission studies<br>[composite load modeling, aggregated distributed energy resource (DER) models emerging]<br>*Gaps:* Energy storage and wind as DERs | Can they be easily decoupled – transmission and distribution? |
| | Transmission assumed as ideal sources in distribution studies | Fidelity of power electronics loads and their interaction with other power electronics needs to be determined? |

# Technical Approach: Classification Formulation

## *Existing Dynamic Simulator Properties*

| Simulators | Modeling Domain | Capabilities | Size of study feasible | Time-scales | Co-Simulation | Assessment Methods/ Capabilities Available | Type of studies | Type |
|---|---|---|---|---|---|---|---|---|
| PSCAD | 3-phase time-domain | Transmission, Distribution, Residential, Microgrids;<br><br>Balanced, Unbalanced; | Small number of nodes | EMT (Typical: 10-100 µs, can go to ns) | Using E-Tran to connect to PSSE for EMT-TS<br><br>Using EPOCHS for EMT-communication cosimulation with NS2 | Fixed time-step, trapezoidal integration, multi-phase | HVdc, wind, PV, FACTs, power electronics systems, microgrids | Commercial |

## *Existing Hardware-in-the-loop (HIL) Simulator Properties*

| Simulators | Modeling Domain | Capabilities | Size of study feasible | Time-scales | Co-Simulation | Assessment Methods/ Capabilities Available | Type of studies | Type |
|---|---|---|---|---|---|---|---|---|
| Opal-RT eMEGASIM | 3-phase time-domain | Balanced, unbalanced;<br><br>Transmission, distribution, microgrids | Maximum of 30 3-phase nodes (90 nodes) per core in real-time | EMT (Typical: 10-100 µs) | With Opal-RT systems, RTDS | | | Commercial |

## *Future Study Properties*

| Study-of-Interest | Modeling Domain | Size of study feasible | Time-scales | Co-Simulation | Model Requirements |
|---|---|---|---|---|---|
| Multi-frequency systems (eg, multiple microgrids) | Time-domain | Can be large-scale | EMT | Transmission-Distribution? | Full 3-phase with detailed/average-value models |

# Project Schedule, Deliverables, and Current Status

| Date | Laboratory | Total Budget (USD) | Cost in Q3 (USD) | Remaining Balance (USD) |
|---|---|---|---|---|
| 06/31 (May, June Expenses Included) | ORNL | 150,000 | 22,806 | 127,194 |
| | PNNL | 90,000 | 6,005 | 83,995 |

| Due Date | Task performers | POC | Milestone Type | Milestone Description |
|---|---|---|---|---|
| **FY19-Q3** | **ORNL, PNNL** | **Suman Debnath, Marcelo Elizondo** | **Quarterly** | • **Initial framework {ORNL, PNNL}**<br>• **Initial questions of interest {ORNL, PNNL}**<br>• **Define metrics for characterizing future grids {dynamics – ORNL, steady-state – PNNL}** |
| **FY19-Q4** | ORNL, PNNL | Suman Debnath, Marcelo Elizondo | Quarterly | • Survey commercially-available tools and begin assessing capabilities {dynamics – ORNL, steady-state – PNNL}<br>• Analyze previous studies performed on high-penetration of power electronics {dynamics – ORNL, steady-state – PNNL}<br>• Open-source tools available and assess capabilities {dynamics – ORNL, steady-state – PNNL}<br>• Reach out to the outreach team {ORNL, PNNL} |
| **FY20-Q1** | ORNL, PNNL | Suman Debnath, Marcelo Elizondo | Quarterly | • Gather data on available standards<br>• Open-source tools available and assess and HIL capabilities {dynamics – ORNL, steady-state – PNNL}<br>• Characterize and assess gaps in tools to analyze future grids {dynamics – ORNL, steady-state – PNNL}<br>• Report the developments {ORNL, PNNL} |

*Q3 milestones successfully completed*

# Anticipated Challenges and Risk Mitigation Strategies

| Challenge | Mitigation Strategy |
|---|---|
| Identification of properties in open-source tools | Utilization of outreach questionnaire to developers and users to identify properties and shortcomings |
| Identifying properties of future grids | Literature survey and standards that have reported on high-penetration power electronics studies to be utilized along with the expertise at ORNL and PNNL in power electronics and grids, respectively |
| Understanding of future scenarios with high penetration power electronics | Utilize two different scenarios to identify gaps |

# Next steps

- Updates in the following
  - Framework with potential inclusion of intermediate power electronic scenario
  - Entries within the framework (including existing capabilities)
  - Visualization of framework for high-level description
  - Metrics update
- Analyze existing high-penetration power electronics studies
- Identify outreach requirements

# Contact Information

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