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EMT Simulation of PV Plant & EMT-TS Hybrid Simulation of Future Grids

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

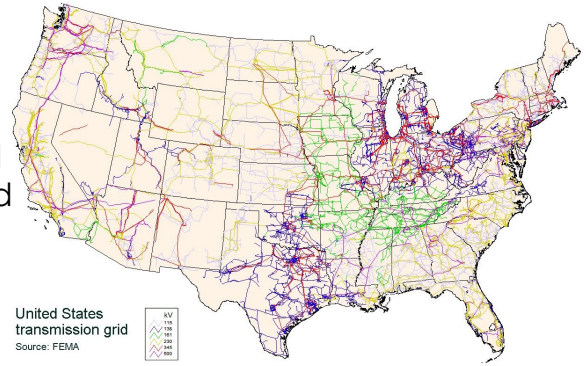
U.S. DEPARTMENT OF ENERGY

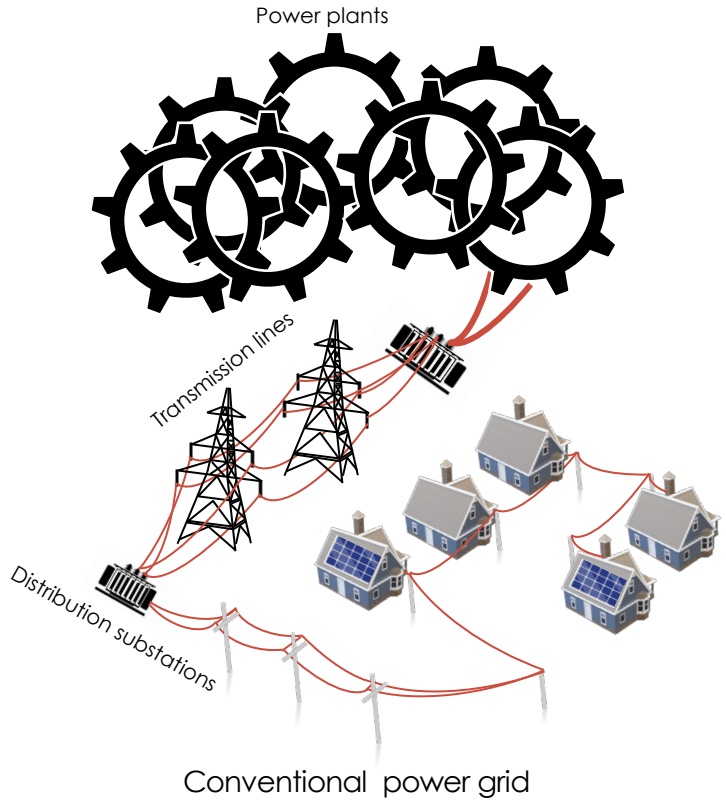
Project Team: ORNL, SCE, PSU, GIT, CAISO, SPP, OGE, FPL/NextEra

Context: Energy System Transition

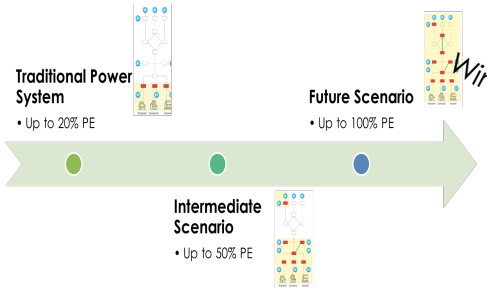
Future US energy system and power grid (real-world system) transition to a **PE-dominated** system

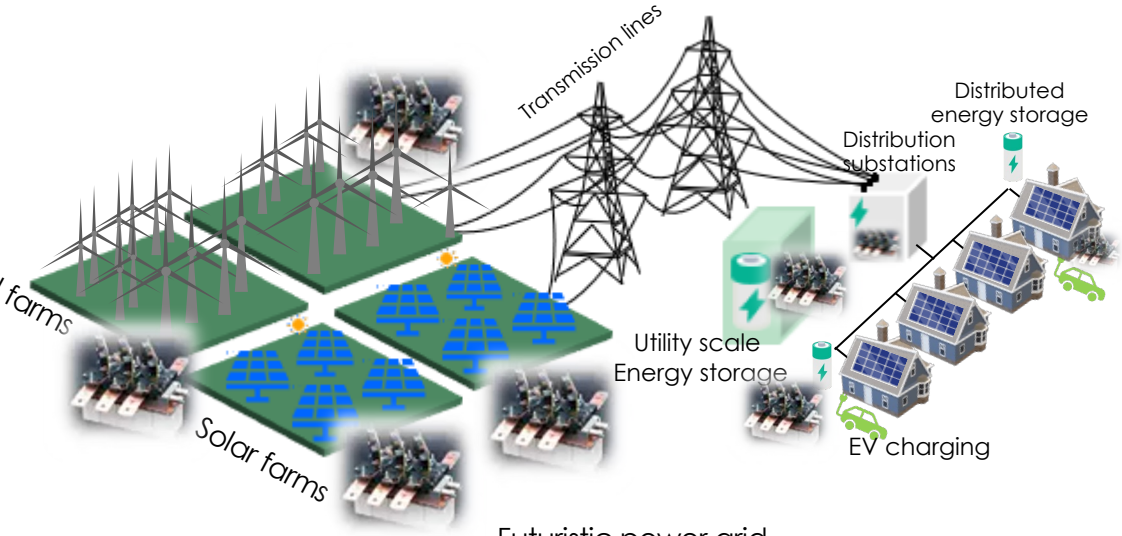
- 22,000 generators,
- 55,000 substations,
- 160,000 miles of high-voltage power lines, and
- Millions of miles of low-voltage power lines and distribution transformers





Conventional power grid



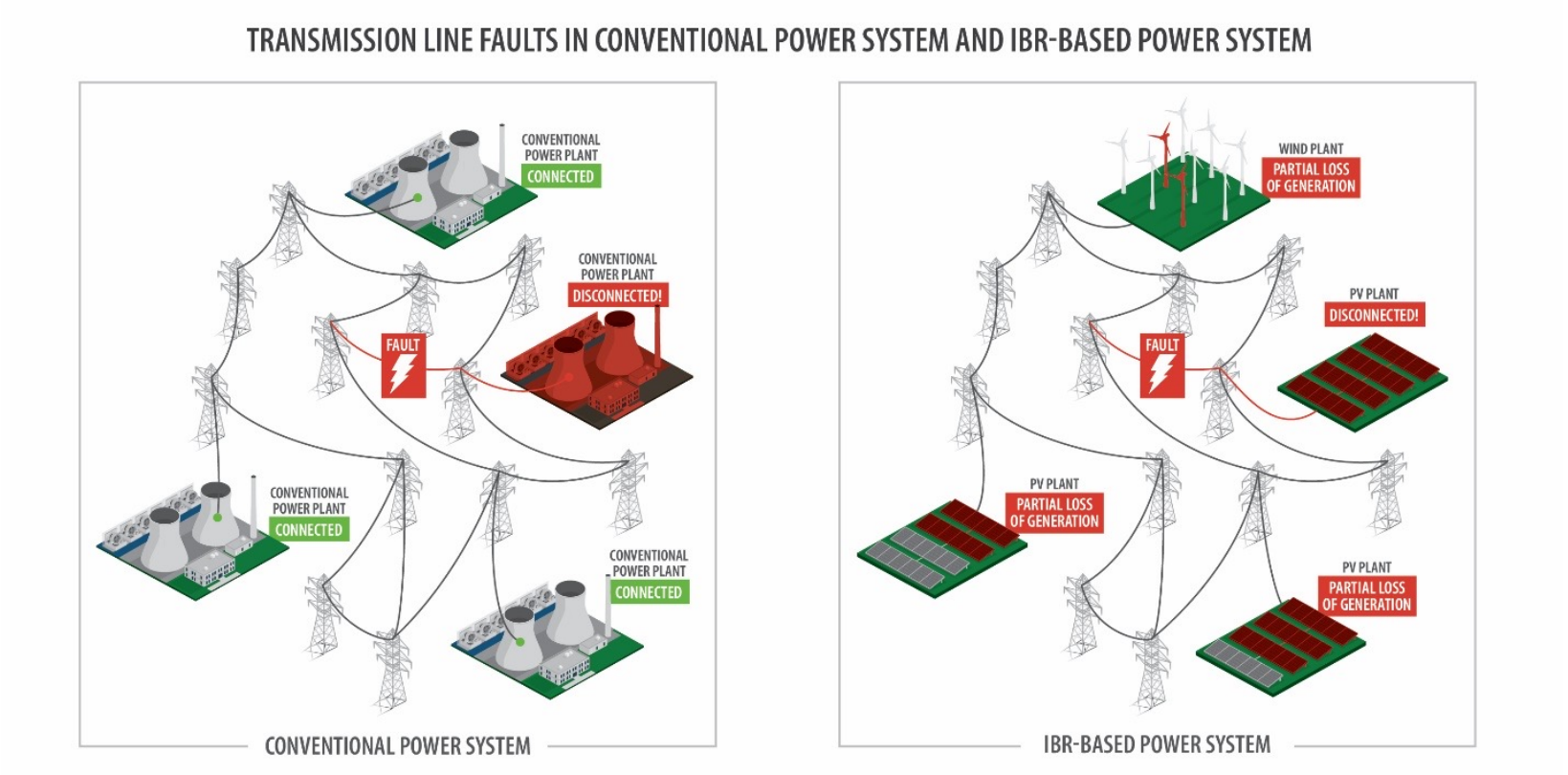


Futuristic power grid

PE – Power Electronics

Challenges Observed

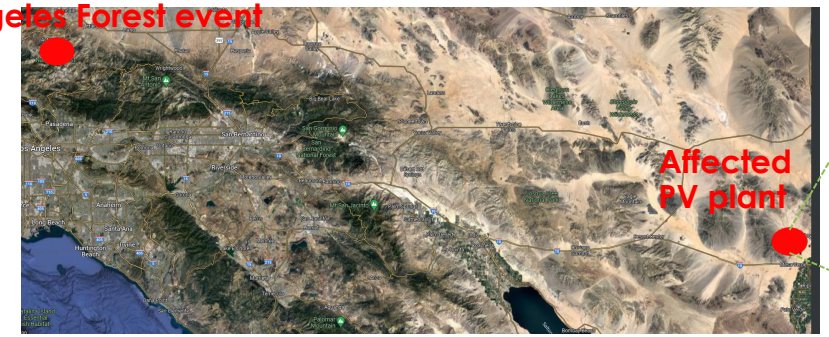
- Partial reduction in power generated by IBRs over a larger region during transmission line faults



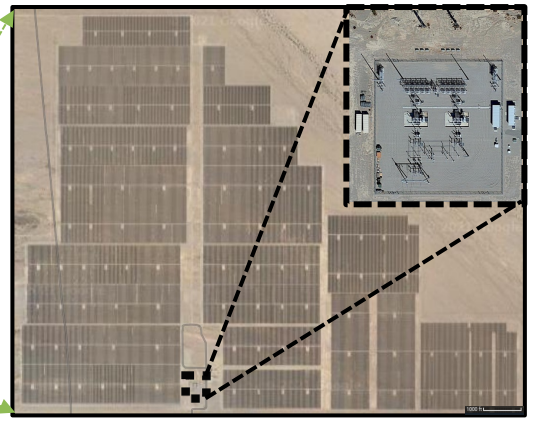
IBR – Inverter-Based Resource

Application: Near-Term Example of Post-Event Replication

- **Goal:** Replicate event in EMT simulations
  - Replicate phenomena in 1 PV plant
  - Replicate grid measurements observed



Courtesy: Google maps and NERC*



Specific PV plant-1 (One of the affected PV plants during Angeles Forest fire event)

- **Approach:** High-fidelity EMT & EMT-TS simulations
  - EMT simulation model of power grid in the region affected by fault
  - High-fidelity switched system model of PV plant with all inverters
  - EMT-TS simulations for large power grid analysis
  - Comparison of high-fidelity models with quasi-dynamic models

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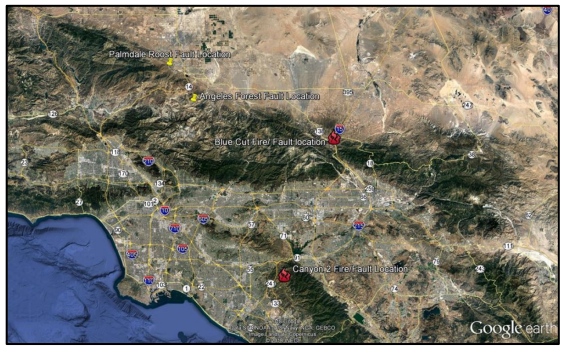
Project: LAMP project with Solar Energy Technologies Office (SETO) in US Department of Energy

PV – Photovoltaic

Application: Near-Term Example of Post-Event Replication

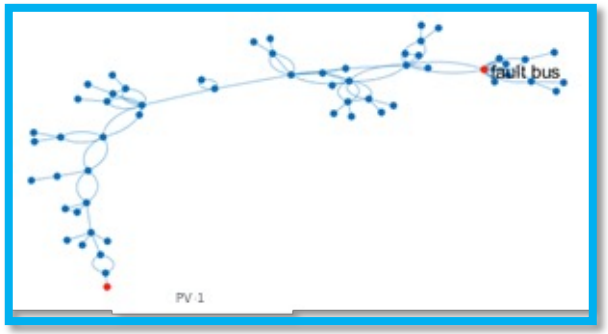
- **Approach Overview:** Develop EMT model of power grid and high-fidelity EMT dynamic model of affected PV plant. Integrate them and evaluate in EMT

EMT Model of Power Grid:



Courtesy: NERC*

Grid disturbances from fire events that led to line-to-line fault



Generate EMT model of power grid from the location of fault to one of the affected PV plants studied from existing models in TS and upgrade the models to incorporate more fidelity in the model of lines, transformers, breakers, and line configurations

Two EMT models developed
- min bus case (connecting fault to PV plant)
- best case (more buses near PV plant and near fault location)

TS – Transient Stability

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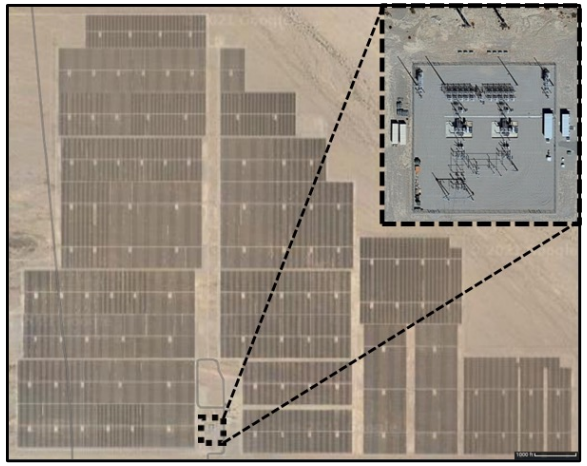
Application: Near-Term Example of Post-Event Replication

High-Fidelity EMT Dynamic Model of PV Plant:



Specific PV plant-1 (One of the affected PV plants during Angeles Forest fire event)

High-Fidelity Models

- Hundreds-thousands of inverters
  - Non-linear non-autonomous hybrid switched-system models
- Hundreds of distribution transformers
- Many distribution lines
- ***Represent partial momentary cessation and shutdown (or during ride-through)***

Challenges

- ***Time consuming nature*** of running these simulations in traditional simulators using library models (e.g., **very long time to run 0.1 s** in a large PV plant model)

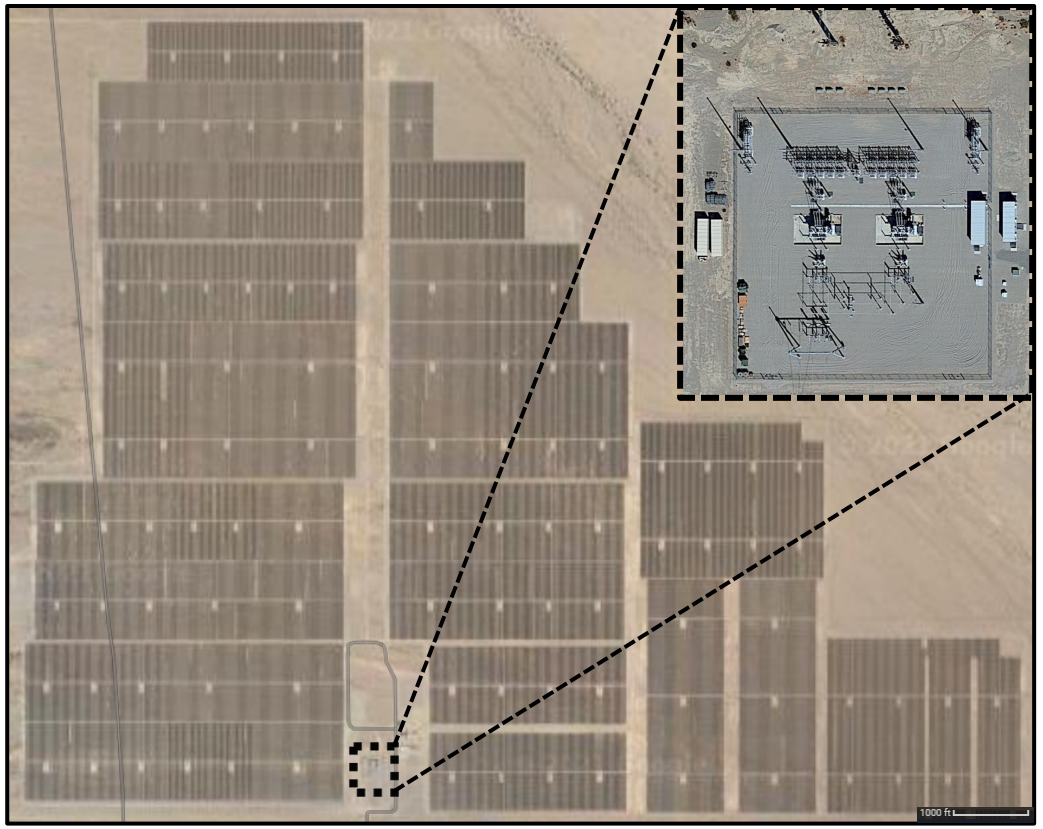
Solution

- Use ***advanced numerical simulation algorithms*** to speed-up simulations**

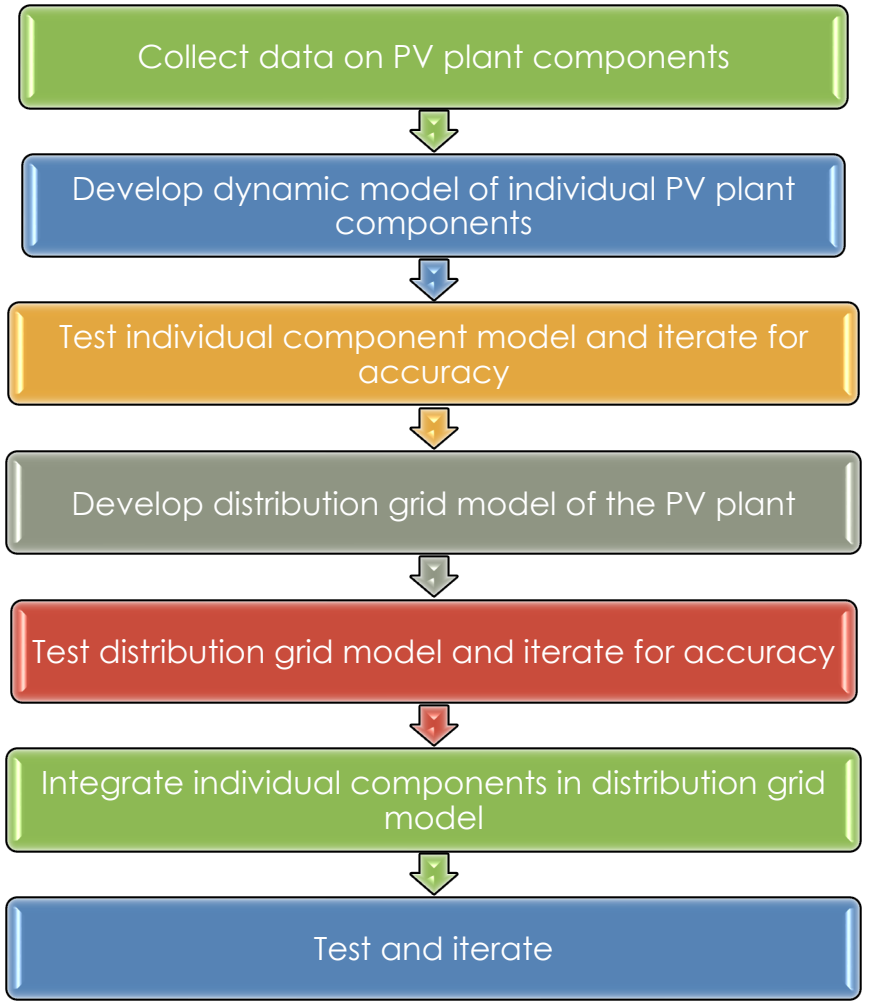
**J. Choi and S. Debnath, "Electromagnetic Transient (EMT) Simulation Algorithm for Evaluation of Photovoltaic (PV) Generation Systems," 2021 IEEE Kansas Power and Energy Conference (KPEC), 2021, pp. 1-6.

Approach: EMT Simulation of PV Plant

- High-fidelity model in PSCAD – development process
  - Specific PV plant-1 with ***hundreds*** of PV, inverters, inverter controllers, transformers, filters, lines



Specific PV plant-1 (One of the affected PV plants during Angeles Forest fire event)

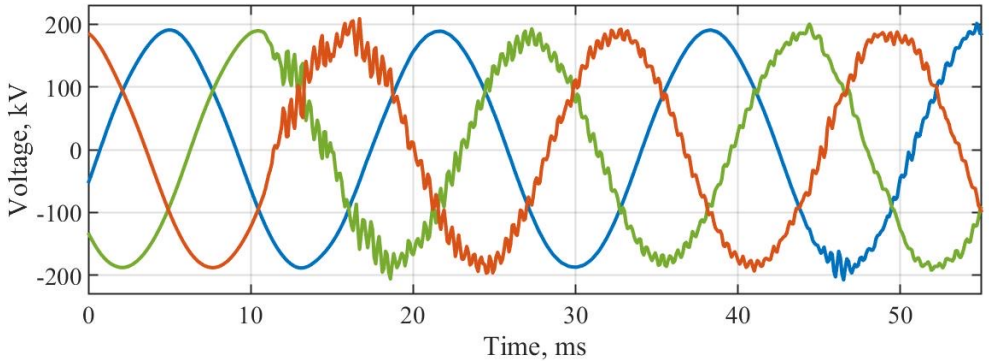


High-fidelity PV plant model development process

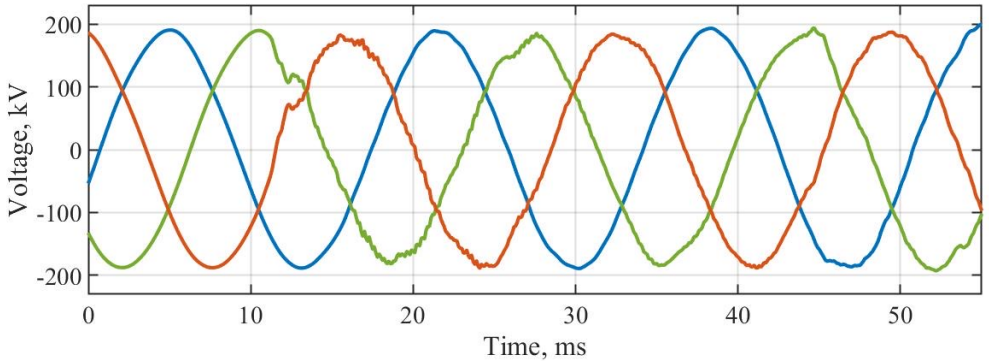
PV – Photovoltaic

EMT and EMT-TS Simulation of PV Plant w/ Grid: Results

ac high-voltage dynamics during fault: min bus case vs best case

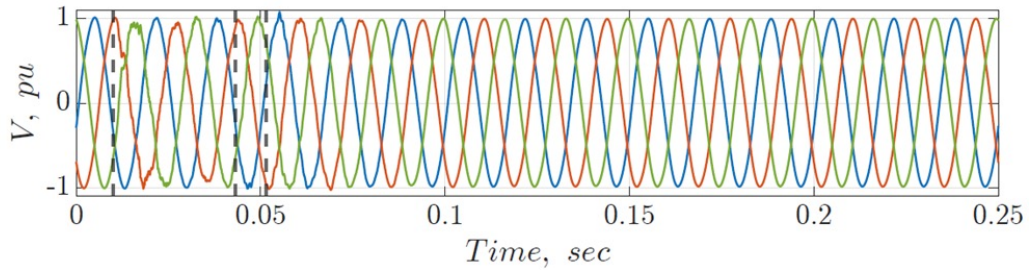


ac high-voltage dynamics during fault (min bus case)

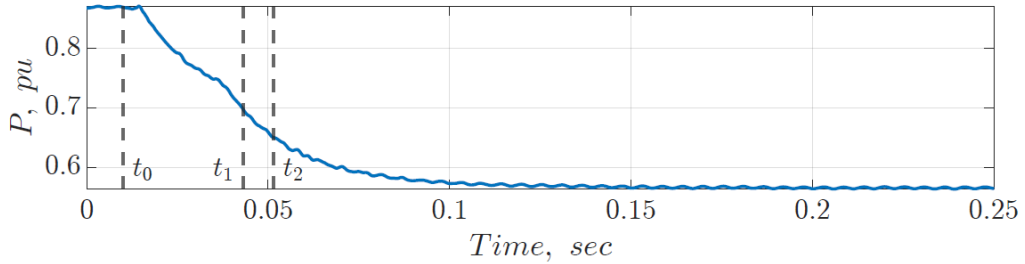


ac high-voltage dynamics during fault (best case)

EMT-TS simulation results with best case



ac high-voltage dynamics during fault



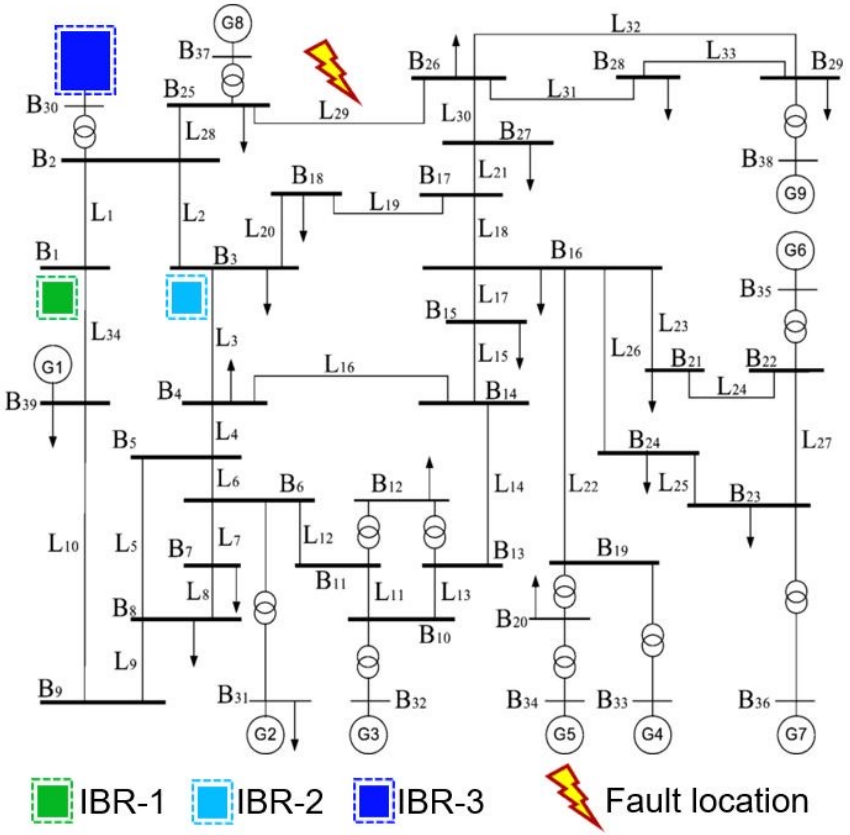
Active power output

Higher accuracy in the simulation results closely replicating the original Angeles Forest response

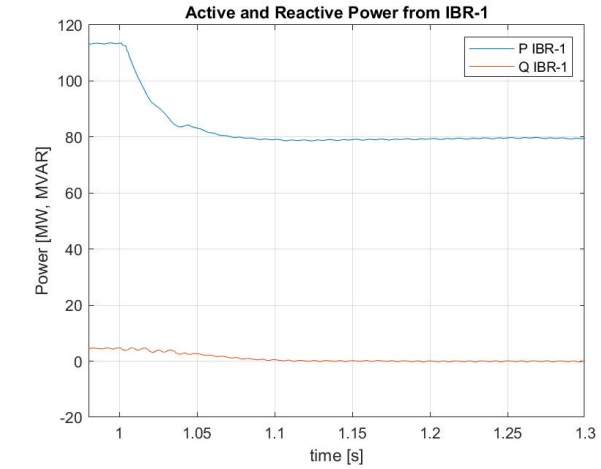
Improved HV-side voltage dynamics; partial power loss exactly similar as in the case of Angeles Forest event

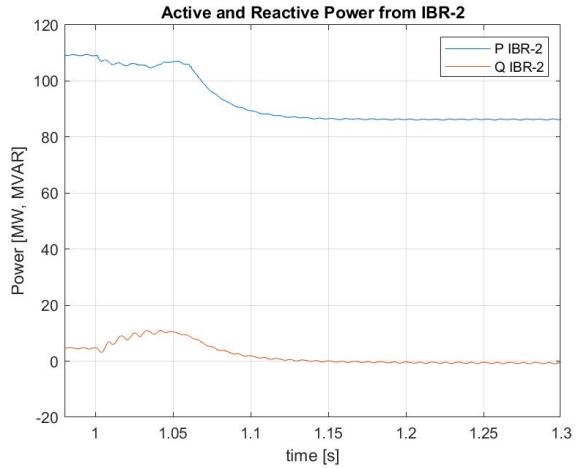
Planning Studies Performed: Multiple IBR Case Study

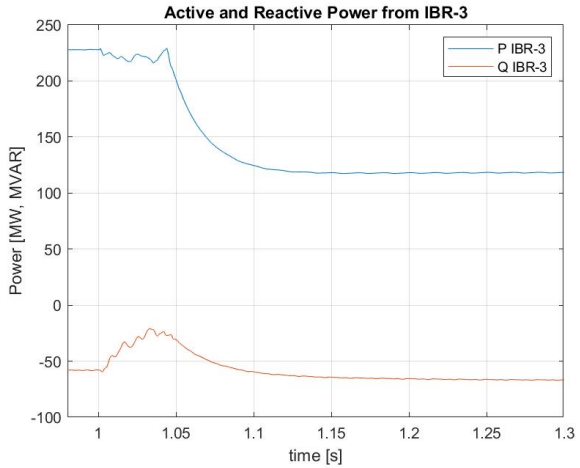
- Fault studies to replicate partial loss of power generation from IBRs (line-to-line)
- Model: high-fidelity EMT model of IEEE-39 bus with **3 IBRs**, **500 inverters**
- Test Cases: line-to-line fault



Layout of IEEE-39 bus system with 3 IBRs







Simulation results for IEEE-39 bus system with 3 IBRs

Partial power loss is observed in all the PV plants; ***Only possible when all the PV plants are modeled HF EMT dynamics models***

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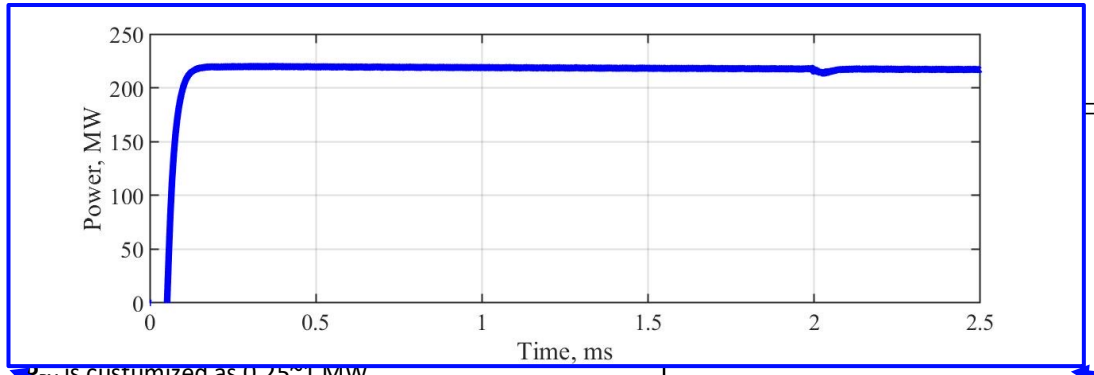
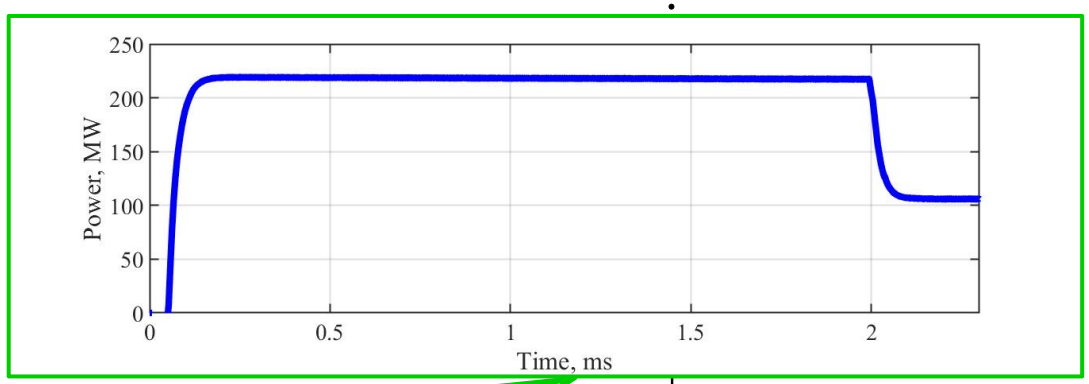
Project: Reliability project with Applied Grid Modeling (AGM) program in U.S. Department of Energy's Office of Electricity (OE).

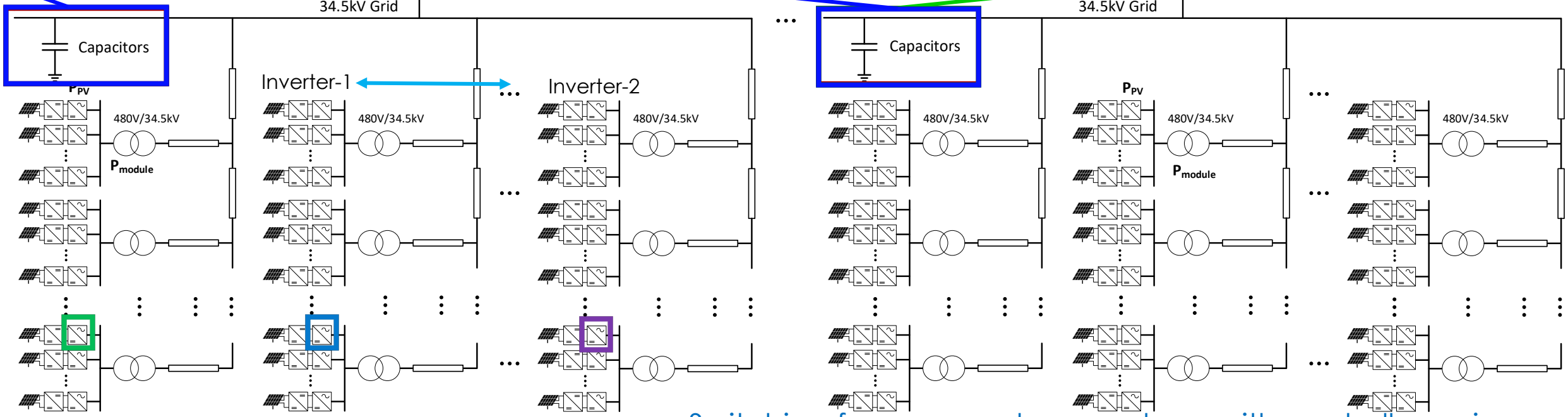
"What-if" Scenarios: Example

- Sensitivity analysis ⋮





P_{PV} is custumized as 0.25~1 MW.



Capacitors: sensitivity analysis

Filter analysis: 2x, 5x

Switching frequency change along with controller gains

Inverter interchanges

Protection algorithms in inverters

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Project: LAMP project with Solar Energy Technologies Office (SETO) in US Department of Energy

Observations and Recommendations

- EMT HF dynamic model developed is extremely helpful to analyze events in simulations as well as help with performing post-event analysis
- Simulating such models prior to the interconnection of inverter-based resources may also help with avoiding reduction in renewable power generation in the future during disturbances
  - Upgrades in plant
  - Upgrades in grid
- Recommendations
  - System and utility operators should have access to the HF switched system models

EMT-TS Hybrid Simulation: Planning Studies in IBR-Dominated Bulk Power Systems

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Project: LAMP project with Solar Energy Technologies Office (SETO) in US Department of Energy

Introduction/Context

- Context for the need for use of EMT[1]
  - HF[2] EMT PV[3] model indispensable for most NERC[4]-documented events
  - EMT model of regional grid: if computationally feasible
- Notes on existing EMT study framework and capability
  - Computationally expensive
  - Not practical to simulate WECC[5] size system
  - Static equivalencing for the TS[6] portion of the grid
    - Cannot represent fault response of IBR[7]-dominated grids

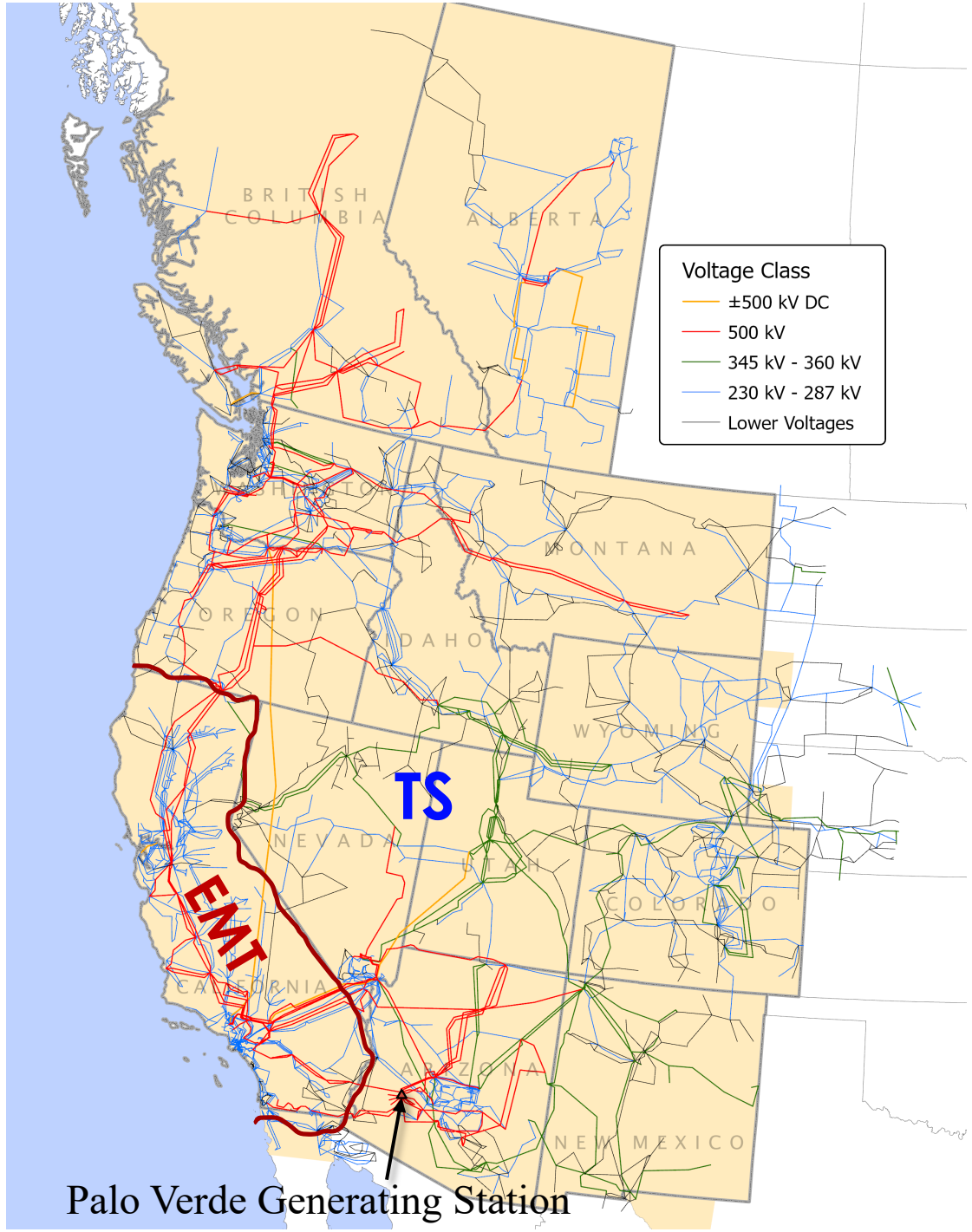
EMT-TS hybrid simulation: can we make best of both worlds in WECC size system studies?

[1]electromagnetic transient; [2]high fidelity; [3]photovoltaic; [4]North American Electric Reliability Corporation; [5]Western Electricity Coordinating Council; [6]transient stability; [7]inverter-based resource

Introduction/Context (contd.)

- Need for use of EMT-TS hybrid simulation
  - Static equivalencing for the TS portion may not be adequate
  - Disturbance events outside EMT zone that can affect IBRs within EMT zone
  - IBR-dominated grids need special attention (and if larger region needs to be analyzed in EMT, there needs to be significant progress in the tool)

EMT-TS hybrid simulation: viable option that retains TS-side dynamics



Approach: EMT-TS Simulation for Planning Studies

PSS/E TS model
- Load flow data (.raw)
- Dynamic model data (.dyr)

Bus numbers for the region to be modeled in EMT
- This can be upgraded in a sequential manner

E-tran conversion

Python based tool

E-Tran generated PSCAD model
- Detailed EMT model for the event location and affected plant
- Equivalent model of the rest of the grid model
- Voltage sources at the boundary buses for hybrid simulation information exchange

Modified PSS/E model
- Removed the buses which are already in PSCAD
- Voltage sources at the boundary buses for co-simulation information exchange
- User defined dynamic model for the plants at the boundary buses

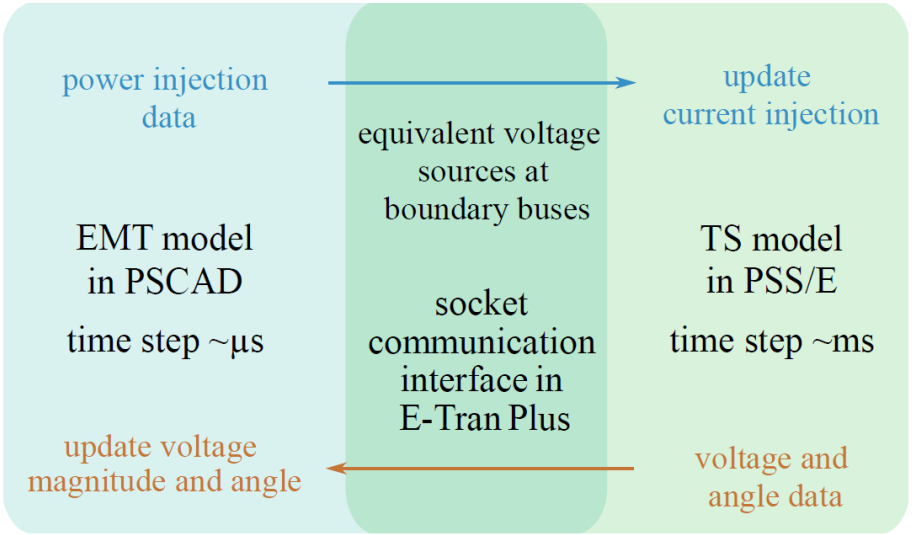
Preparing the hybrid simulation model

Modification in the PSCAD model
- Added renewable plant model
- Added breaker, voltage and current measurements
- Detailed model of the lines if required
- Declare the timing for load, generator, and hybrid simulation initialization in PSCAD model

Case file for running the PSS/E file
1. Initializing and converting loads generators for dynamic simulation
2. Adding event simulation in PSS/E case if necessary

Running the hybrid simulation model

Run the hybrid simulation from PSCAD
- Ensure the steady operating point before hybrid simulation.
- Event study and save simulation results for post processing.



EMT-TS hybrid simulation: Requires PSS/E, PSCAD, E-Tran, and E-Tran Plus

Upgradations of EMT zone is an iterative process

Present grid scenario: 1 HF PV model

Information extraction about the fault event:

Identify the faulted line, buses, and affected PV plant

↓

Min bus case EMT model :

Create an EMT model which includes the fault location, affected PV plants, and buses in the minimum spanning tree from fault to PV plant.

↓

Improving response near the fault:

Add details in the EMT model near the fault location- add transmission line details, breakers, shunt devices, etc.

↓

Improving response near the affected PV:

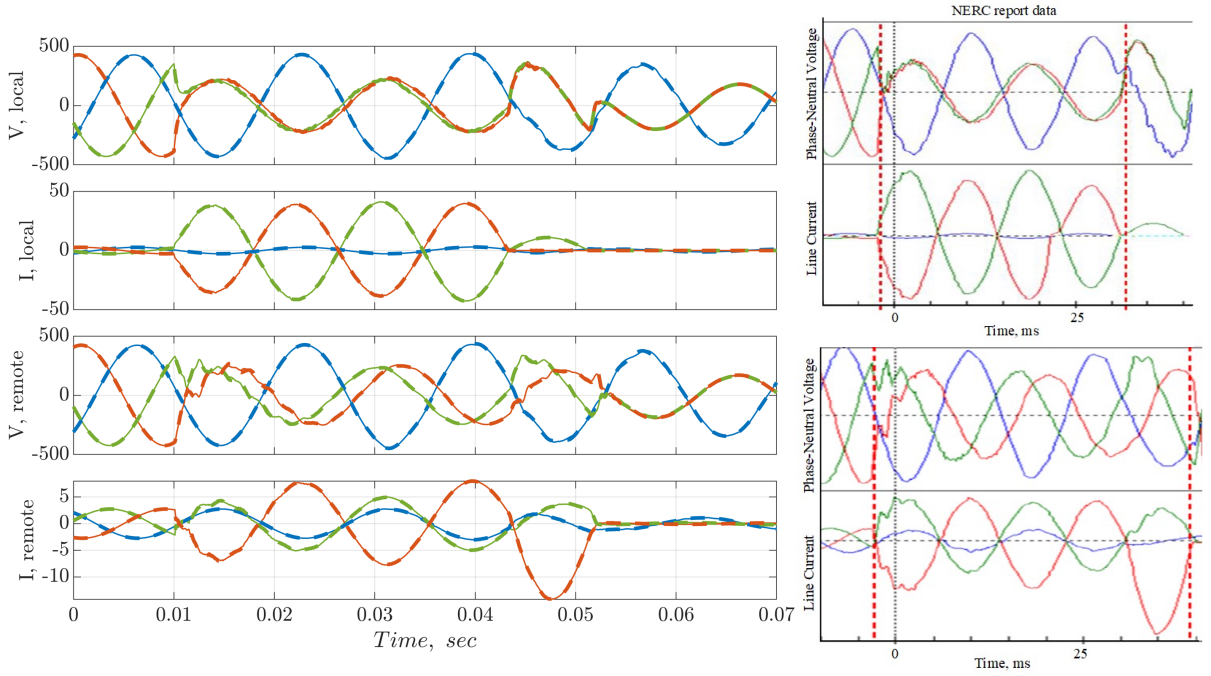
Add more buses, synchronous generators, transformers, loads near the affected PV plant.

↓

Add detailed PV model:

Detailed model of PV plant to replicate the partial generation loss during the disturbance.

EMT-TS: min bus (solid) vs best (dashed)



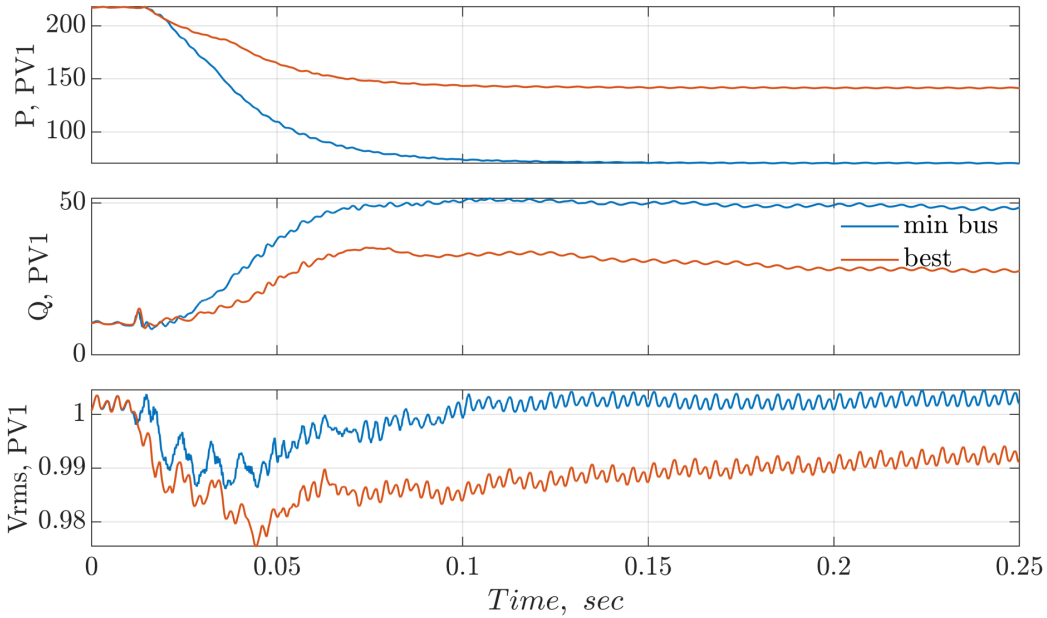
Extent of EMT region needs careful calibration

>95% accuracy w.r.t. field data

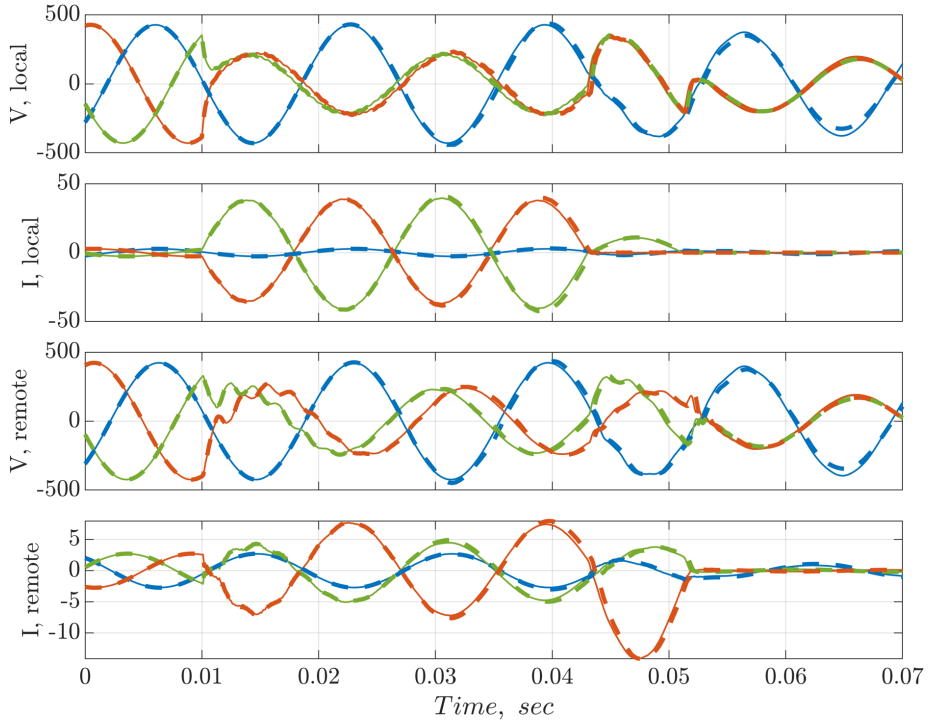
Voltages in kV, currents in kA

Present grid scenario: 1 HF PV model

EMT-TS: min bus (blue) vs best (orange)



Best: EMT (solid) vs EMT-TS (dashed)

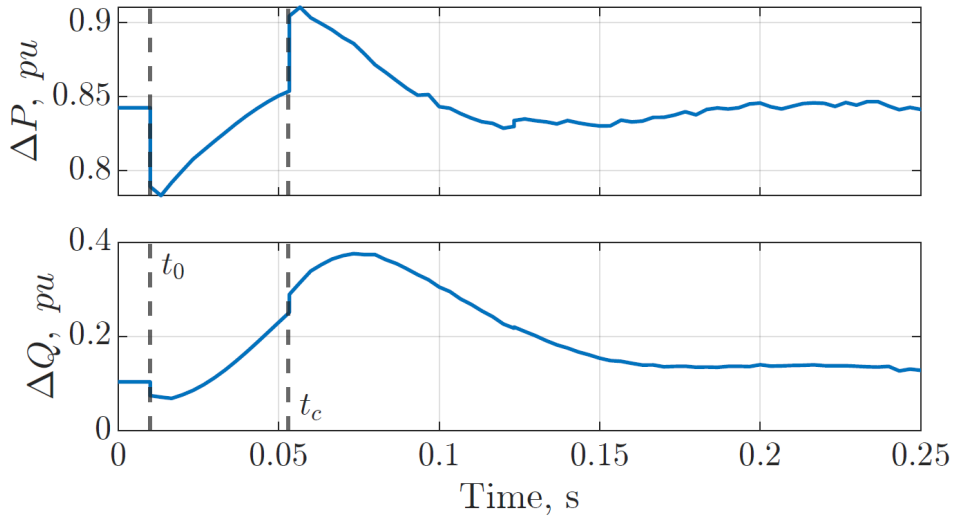


Extent of EMT region needs careful calibration

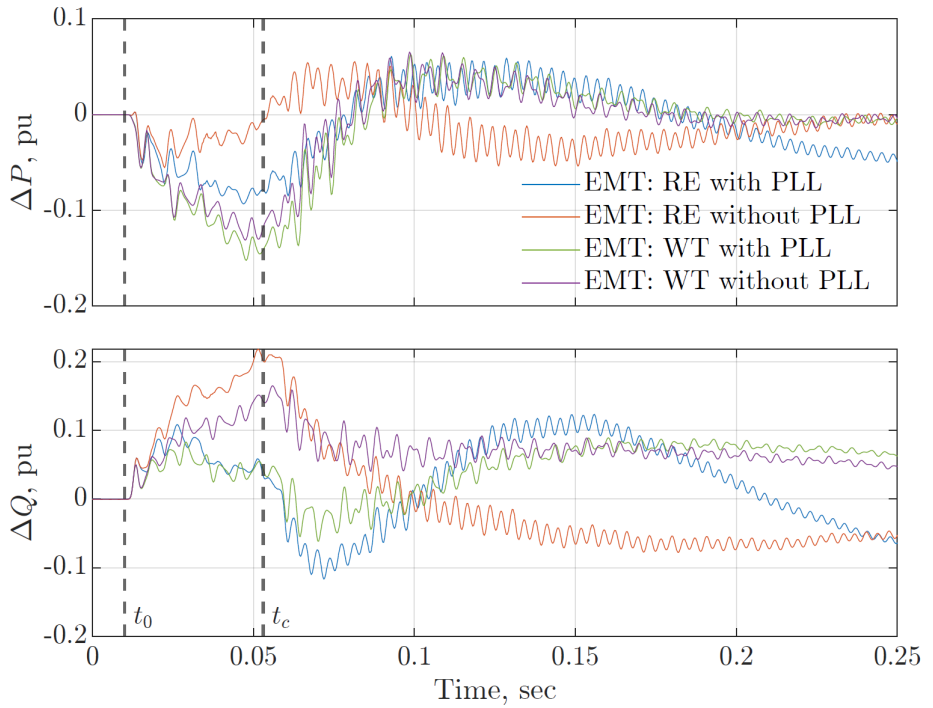
EMT and EMT-TS results very close in these plots

Voltages in kV, currents in kA

QDM[1] and Equivalent model comparison

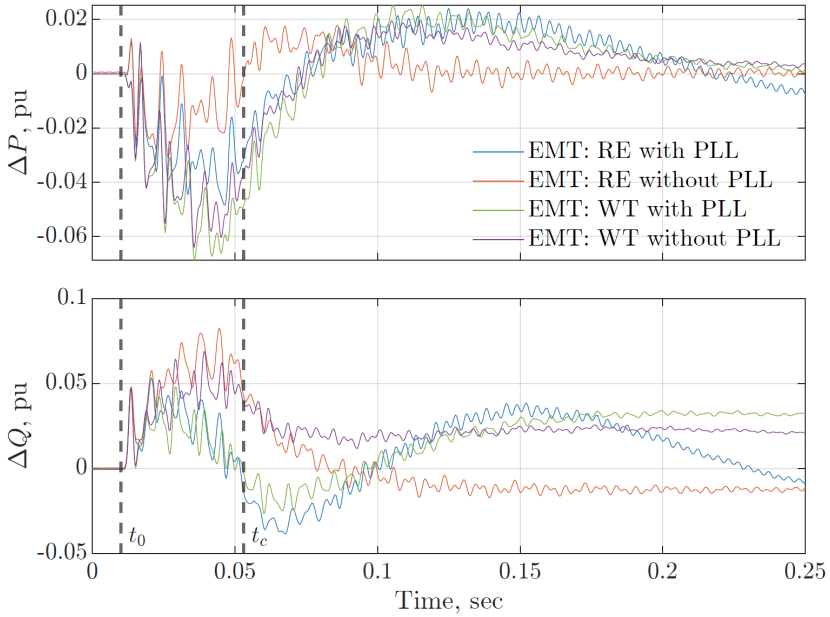


QDM: PSS/E WT model under symm. fault



Eq. model: PSCAD WT/RE models under symm. fault

Eq. model: PSCAD WT/RE models under Angeles Forest (unbalanced) fault

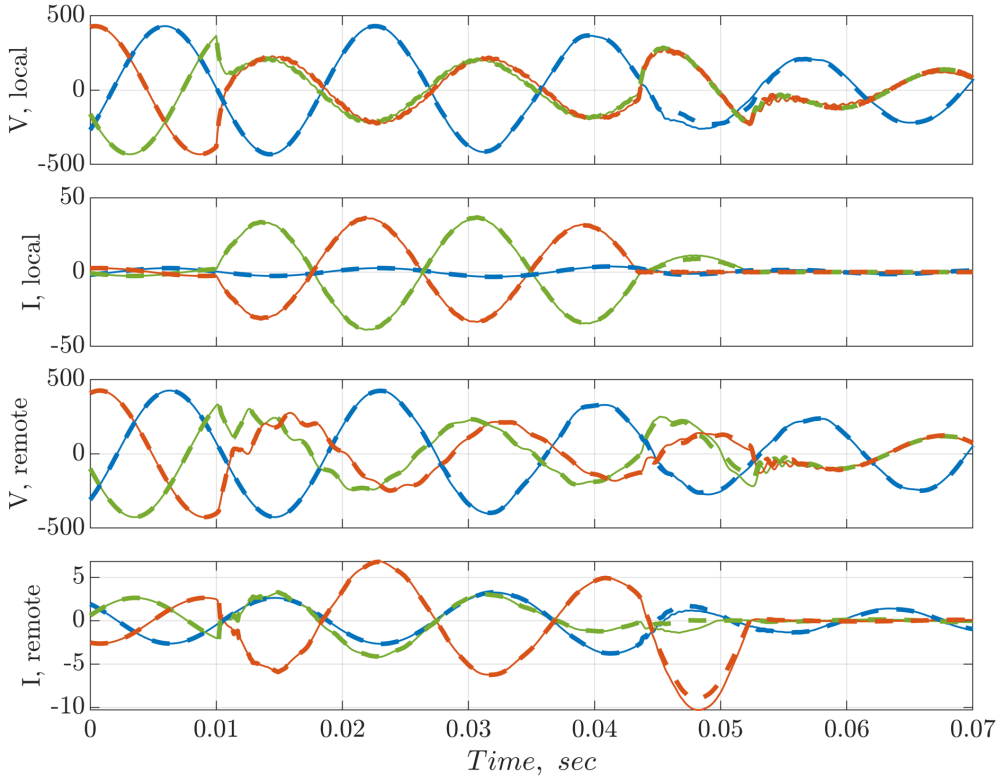


QDM and Equivalent models cannot capture partial generation loss: HF PV plant model needed

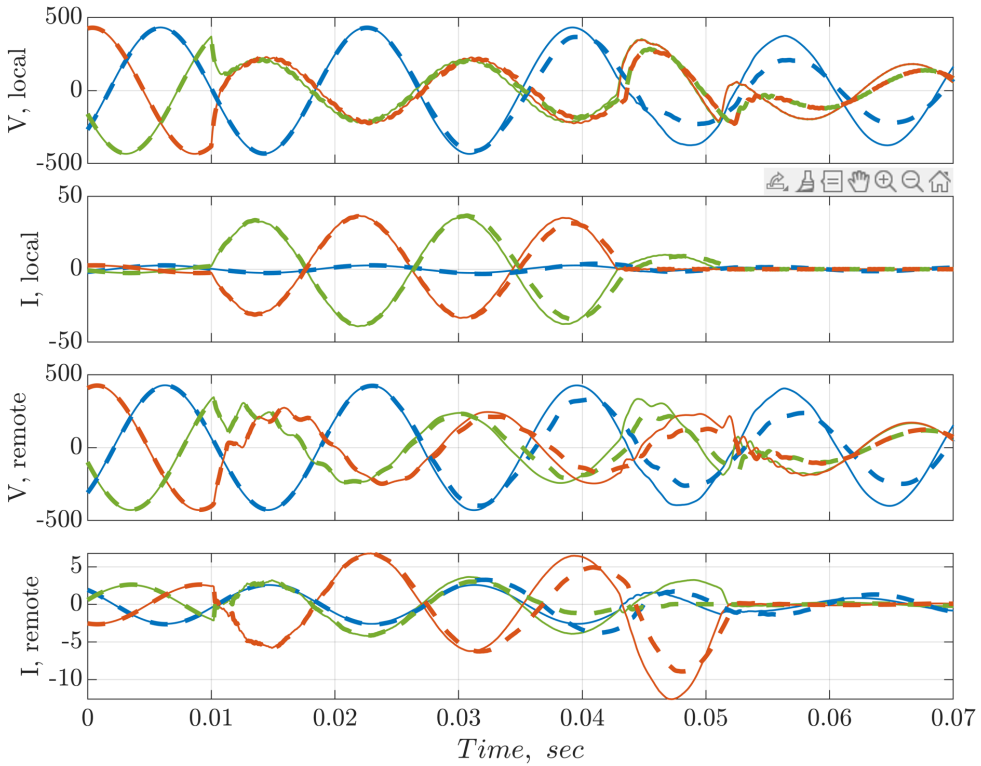
[1]quasi-dynamic model

60% renewables in California: 2 HF PV models

EMT-TS: min bus (solid) vs best (dashed)



Best: EMT (solid) vs EMT-TS (dashed)



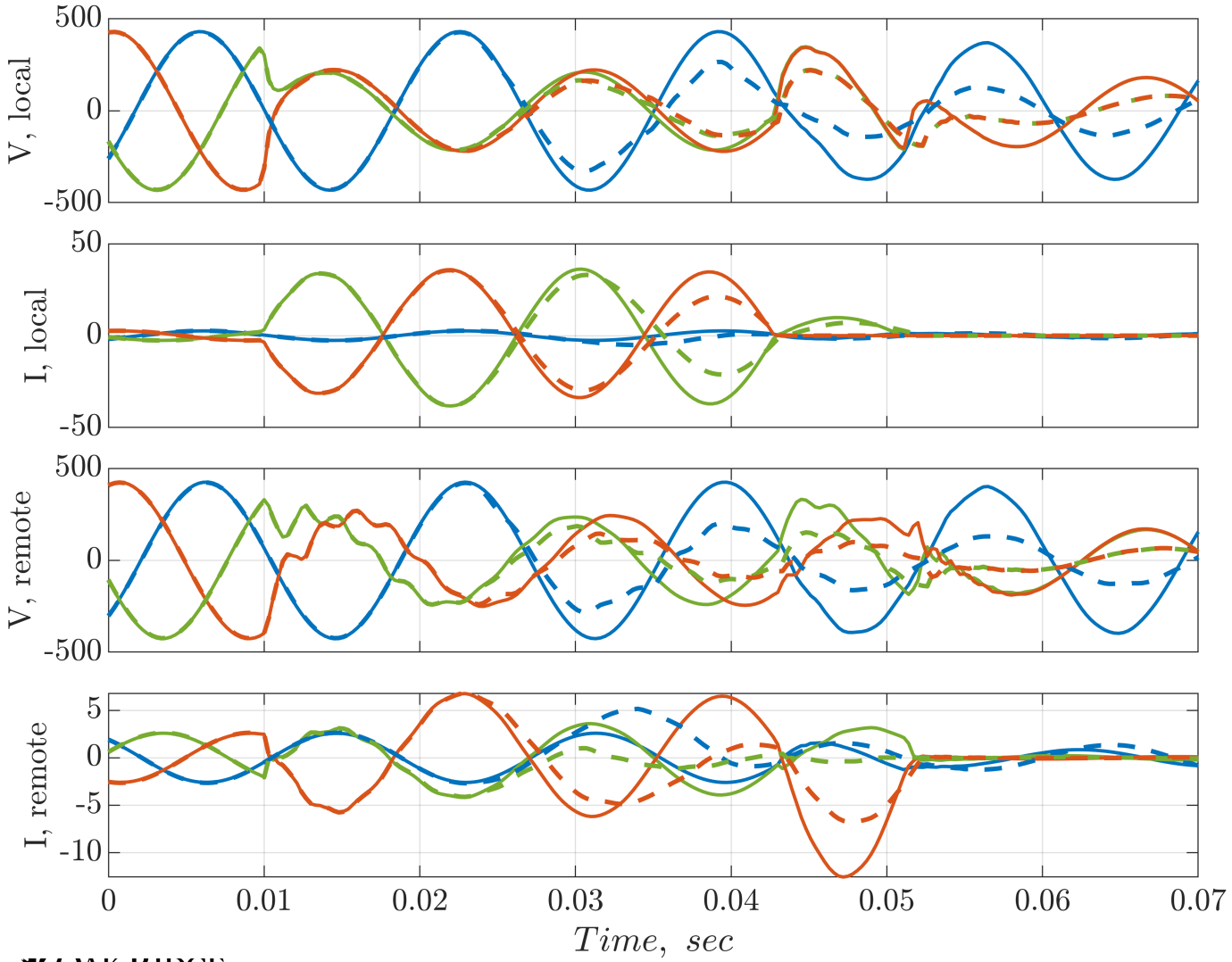
Extent of EMT region needs careful calibration

Static equivalence of IBR-dominated grid in EMT-only simulation needs evaluation

Voltages in kV, currents in kA

Preliminary study: 100% renewables in California

- Angeles forest disturbance: EMT-TS (dotted)vs EMT only (solid)



Static equivalence of IBR-dominated grid in EMT-only simulation needs further evaluation

Voltages in kV, currents in kA

Lessons Learnt

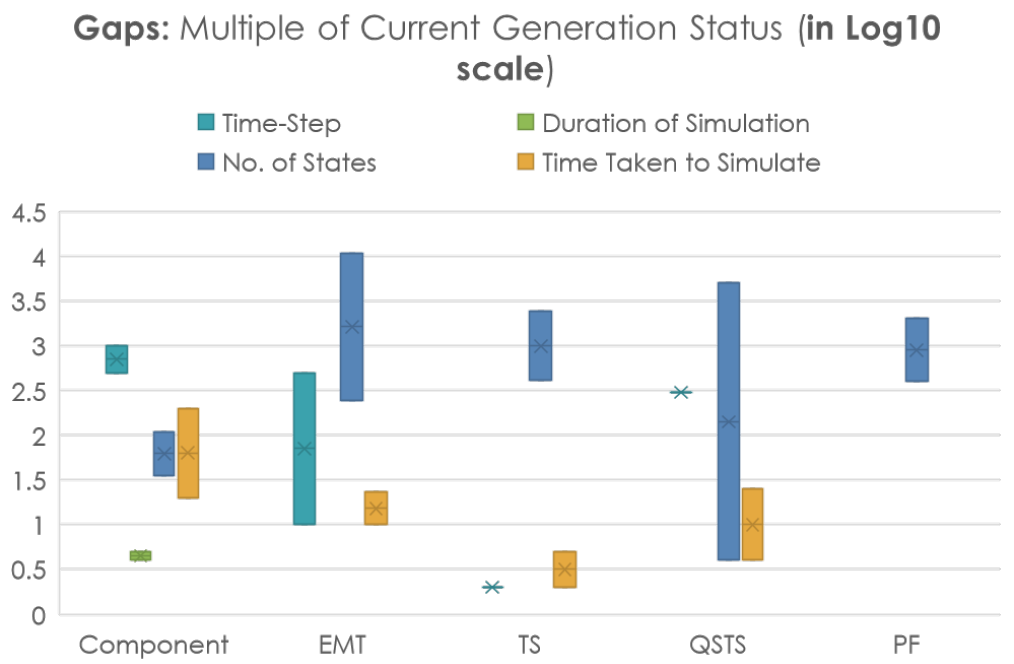
- The gaps in the EMT simulation and modeling indicate the need for increased computing resources and efficient algorithms to simulate future scenarios of grids
- Several orders-of-magnitude improvement is needed in dynamic simulators (EMT, components) to enable planning and operation of future electric grids with high penetration of power electronics
- EMT-TS hybrid simulation provides an alternative future planning tool until EMT simulation can be scaled and the need arises

Impact

- Replicate the event that happened in the power grid using high-fidelity and EMT simulations
- Enhance the understanding in the community with the type of models necessary in the power grid and power plant
- Continued conversation with NERC for improved models

Gaps & Challenges Observed

- EMT Requirements:
  - The requirement of decreased time-steps
  - Increased number of states to be simulated
  - Decreased time taken to simulate
  - Leap of faith compute capability required for very large-scale simulation to simulate in reasonable time-frame without convergence challenges
- Area to be converted in EMT portion is limited to a certain number of nodes
- Model conversion deficiency in EMT from TS exists



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Report: Suman Debnath, Marcelo Elizondo, Yuan Liu, Phani Marthi, Wei Du, Shilpa Marti, Qiuhua Huang, "High Penetration Power Electronics Grid: Modeling and Simulation Gap Analysis", ORNL Technical Report, 2020.

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