High Fidelity Modeling of Large-scale PV plant (IBR) for EMT Simulations

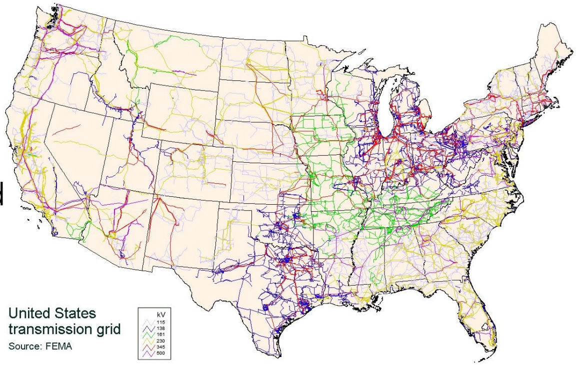
Suman Debnath

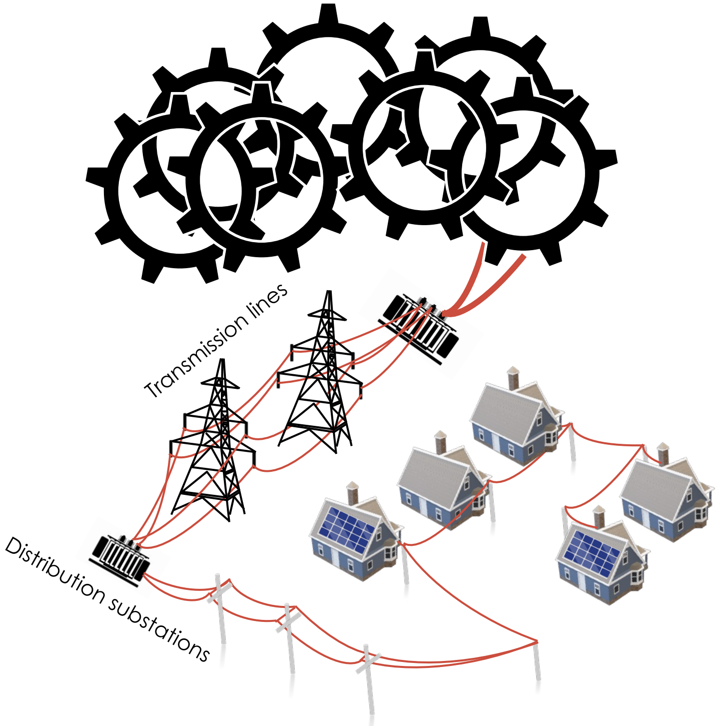
Jongchan Choi

Context: Energy System Transition

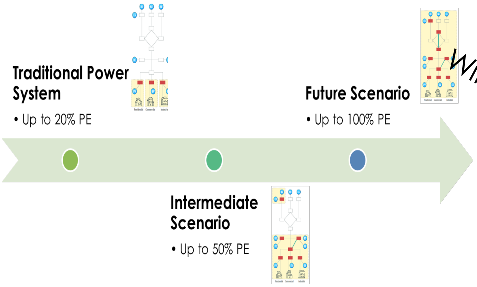
Future US energy system and power grid (real-world system) transition to a **PE-dominated** system

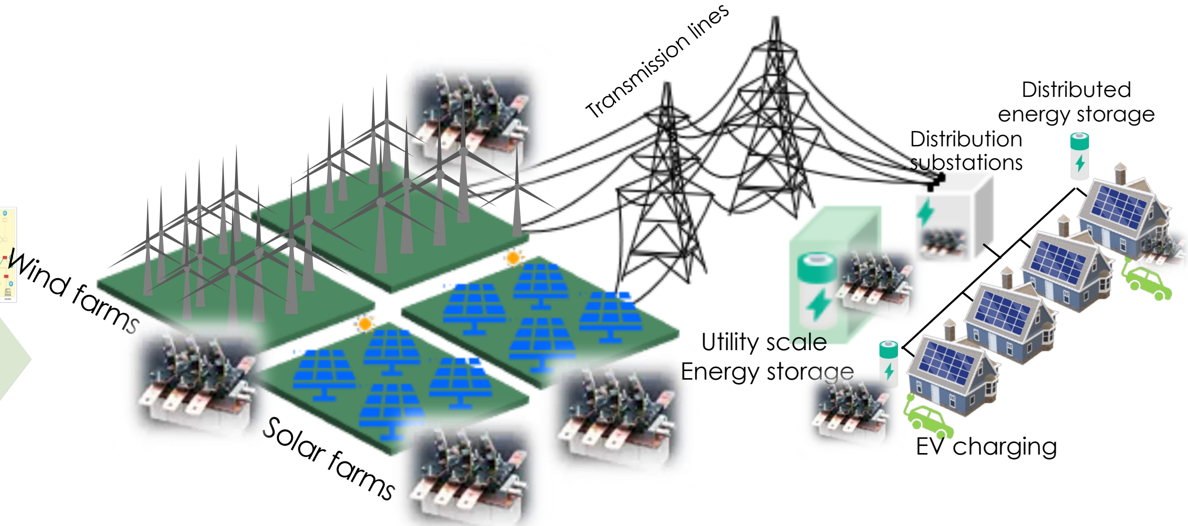
- 22,000 generators,
- 55,000 substations,
- 160,000 miles of high-voltage power lines, and
- Millions of miles of low-voltage power lines and distribution transformers





Conventional power grid





Futuristic power grid

PE – Power Electronics

Context: Energy System Transition

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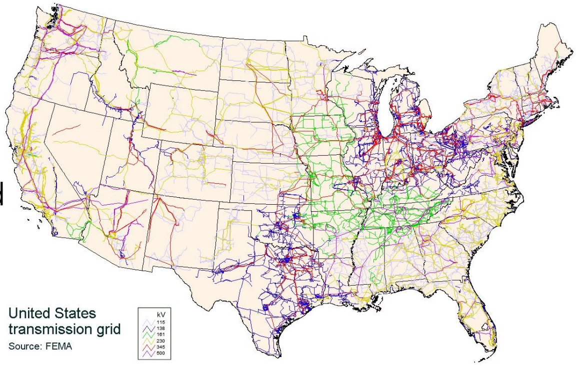
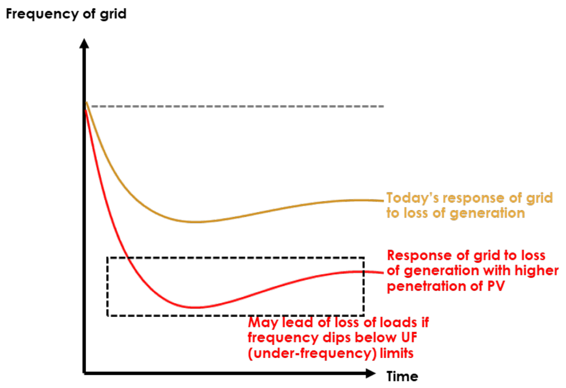
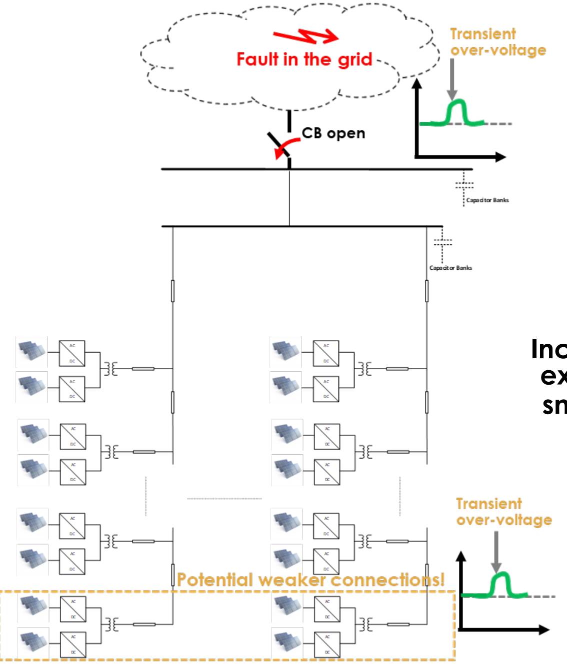
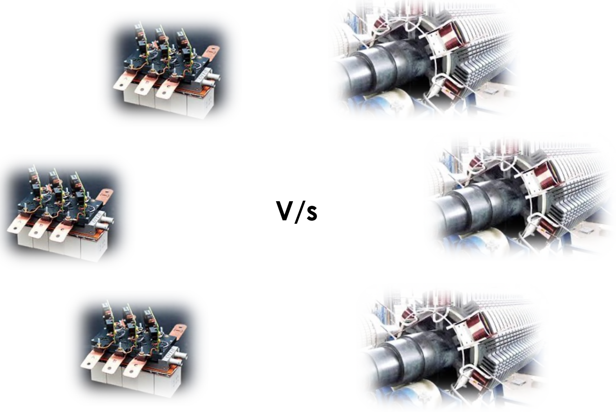


Challenges Arising





Increased vulnerability to external disturbances in small timesteps with PEs



Reduced short circuit strength of power grid

Context: Simulation Requirements Identified

Needs Identified by NERC: 1. EMT simulations as more power electronics is integrated
2. Higher fidelity models of connected devices in power grid needed


NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

1,200 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report

Southern California 8/16/2016 Event

June 2017

NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

900 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report

Southern California Event: October 9, 2017
Joint NERC and WECC Staff Report

February 2018

NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

April and May 2018 Fault Induced Solar Photovoltaic Resource Interruption Disturbances Report

Southern California Events: April 20, 2018 and May 11, 2018
Joint NERC and WECC Staff Report

January 2019

NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

San Fernando Disturbance

Southern California Event: July 7, 2020
Joint NERC and WECC Staff Report

November 2020

NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

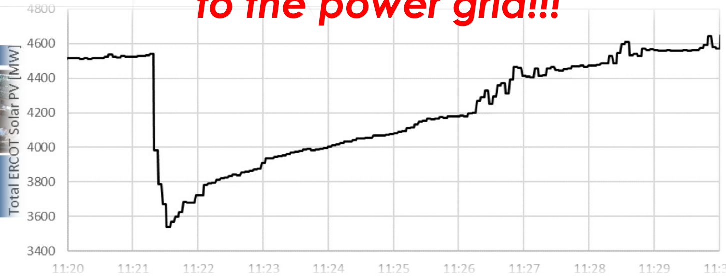
Odessa Disturbance

Texas Events: May 9, 2021 and June 26, 2021
Joint NERC and Texas RE Staff Report

September 2021

2016 **2017** **2018** **2020** **2021**

Reliability challenge to the power grid!!!



Courtesy: NERC

~~Existing TS models are insufficient for modeling disturbances with power electronics~~

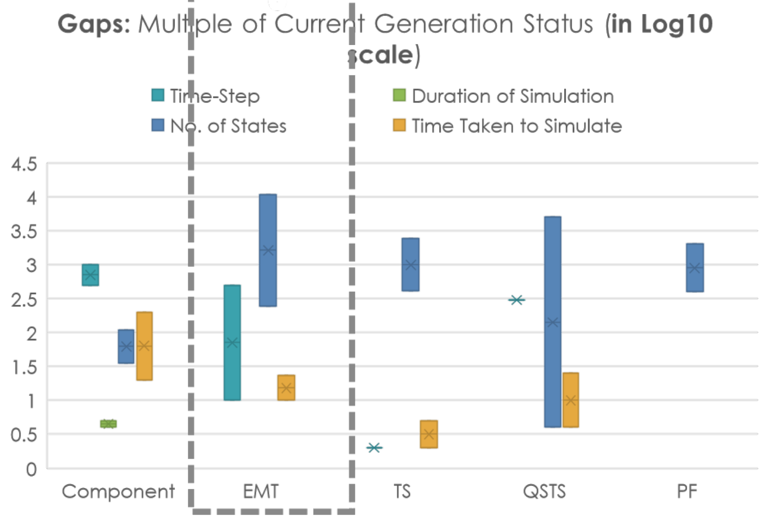
EMT – Electromagnetic Transient
TS – Transient Stability

Simulation Needs: Gaps & Challenges

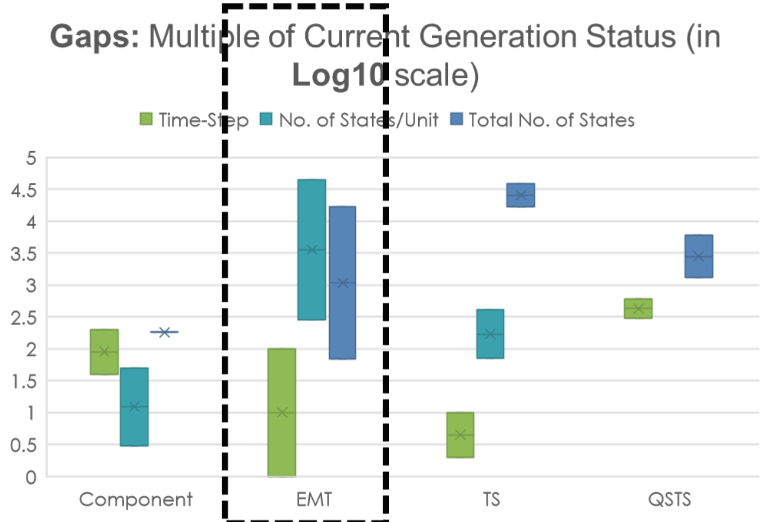
Availability of ***fast high-fidelity simulation models*** of components

Availability of ***real-time small time-step high-fidelity models*** of components

Scale system studies by 100x (~9,000 buses to 1,000,000 buses)



Offline simulators



Real-time simulators

Speed-up required (of the order of 10^6 x) with EMT simulators

Scale system studies by 2,000x (~435 buses to ~1,000,000 buses)

Scale subsystem studies by 10^2 x (~40 bus/unit to ~4,000 bus/unit)

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Suman Debnath et. al. "High Penetration Power Electronics Grid: Modeling and Simulation Gap Analysis", ORNL Technical Report

Ongoing Research

Models: IBRs

- Suite of High-Fidelity EMT Time-Domain Models of Large-Scale PEs (SHIFT-PE)
  - Offline (Fortran, C, C++)
  - Hardware-based (RSCAD, Opal-RT, Multi-Core DSP, GPU)

Applications:

- Reliability analysis: IBRs
- Planning: HVdc
- Event replications

Simulation Tools: EMT

- New numerical and parallelization techniques evaluated
- Simulate higher fidelity of models and larger systems in EMT
- New computing architectures

IBR – Inverter-Based Resources
HVdc – High-Voltage Direct Current
DSP – Digital Signal Processing
GPU – Graphics Processing Unit

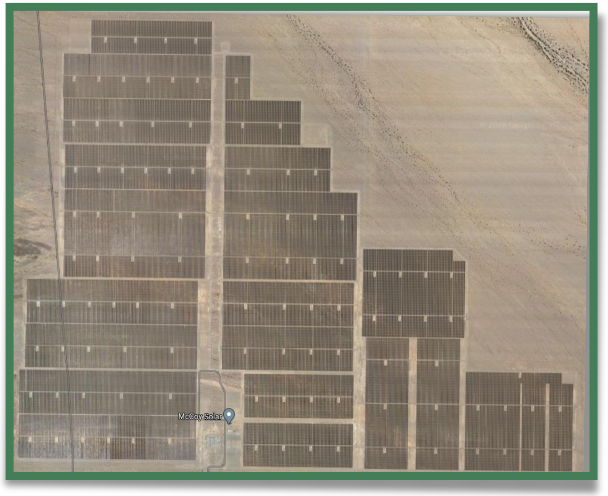
Oak Ridge National Laboratory

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)



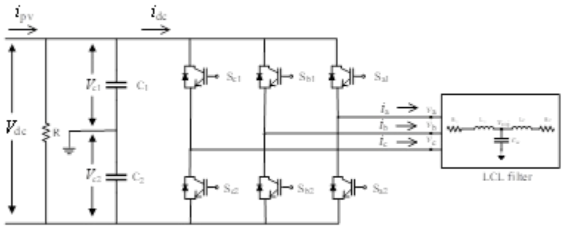
PV Power Plant (100s of inverters, 10s – 1,000 MW)

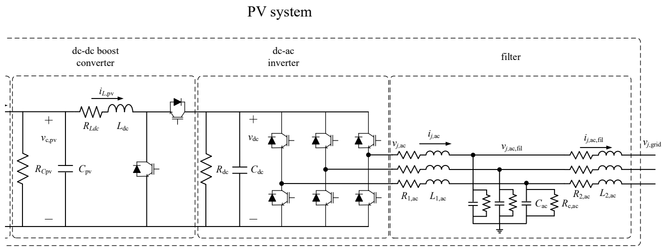
HVdc Substation (2,400 PE modules, 100 – 3,000 MW)

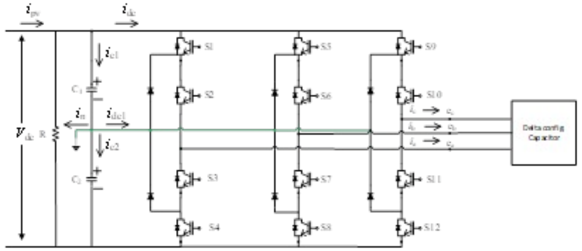
Hybrid Plant (1,500 PE modules, 100 – 2,000 MW)

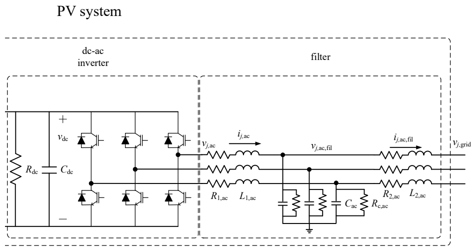
EV Charging Stations (300 chargers in T&D grid)

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)

Oak Ridge National Laboratory

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

Application: Event Description – 2018 Angeles Forest Fire

Courtesy: Google maps and NERC*

Courtesy: NERC*

Reliability Challenge: In the order of nearly 900 MW of PV power generation lost.

Transient AC overvoltage observed at inverter terminals within PV plants during the disturbance (but not at the POI of the plant)!

Partial power reduction observed from most PV plants during the disturbance!

POI – Point of Interconnection

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Challenges with Existing Models

Courtesy: Google maps and NERC*


NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

April and May 2018 Fault Induced Solar Photovoltaic Resource Interruption Disturbances Report

Southern California Events: April 20, 2018 and May 11, 2018
Joint NERC and WECC Staff Report

January 2019

RELIABILITY | ACCOUNTABILITY

3353 Peachtree Road NE
Suite 600, North Tower
Atlanta, GA 30326
404-446-2560 | www.nerc.com

Courtesy: NERC*

- ***Requirement***
  - ***Improved modeling and simulation*** requirements identified to replicate events (post-event analysis, planning, design).
- **Challenges**
  - Aggregated model (**can't replicate** the partial tripping of PV plants).
  - High-fidelity model (**time consuming** due to EMT nature and large number of components).

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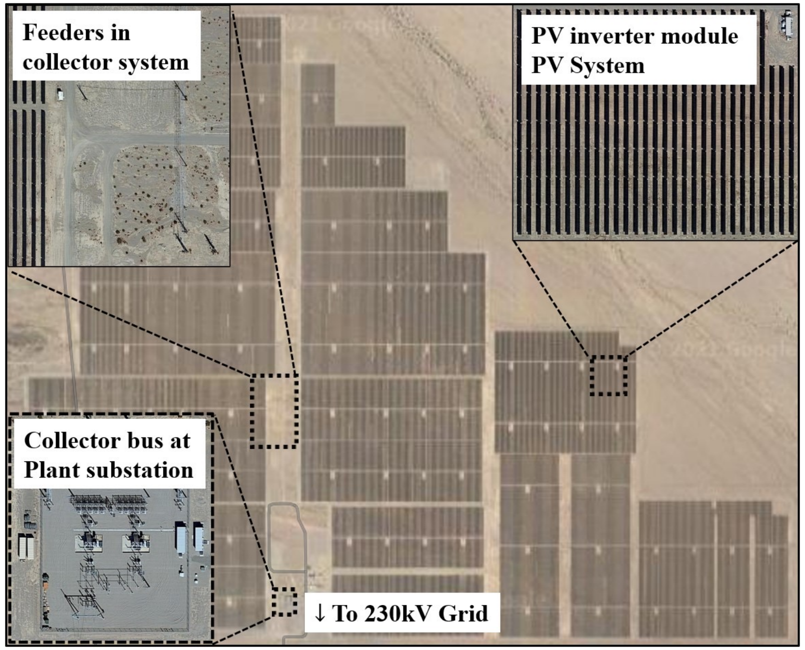
Approach: High-Fidelity Switched System Model

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: Advanced Numerical Simulation Algorithms on High-Fidelity Models

State-Space Approach

Component-1 $\dot{\mathbf{x}}_1 = \mathbf{f}_1(\mathbf{x}_1, \mathbf{u}_1, t)$

⋮

Component-n $\dot{\mathbf{x}}_n = \mathbf{f}_2(\mathbf{x}_n, \mathbf{u}_n, t)$

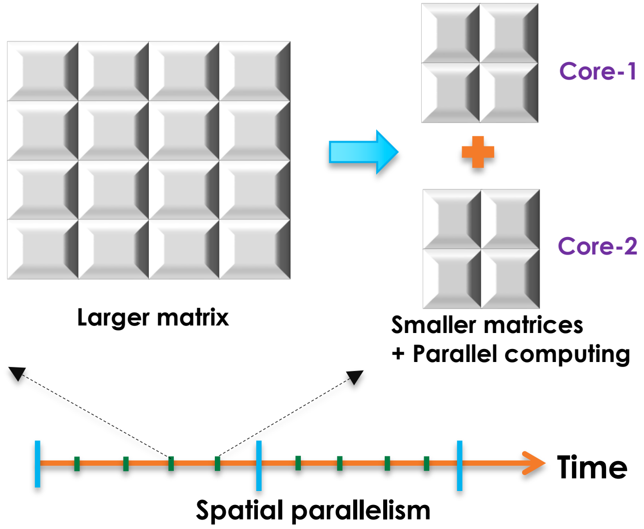
Component DAEs

$\dot{\mathbf{x}} = \mathbf{f}_2(\mathbf{x}, \mathbf{u}, t)$

Combined DAEs for system model

$\mathbf{A}\mathbf{x}[k] = \mathbf{b}$

Discretized and linearized system model using single discretization



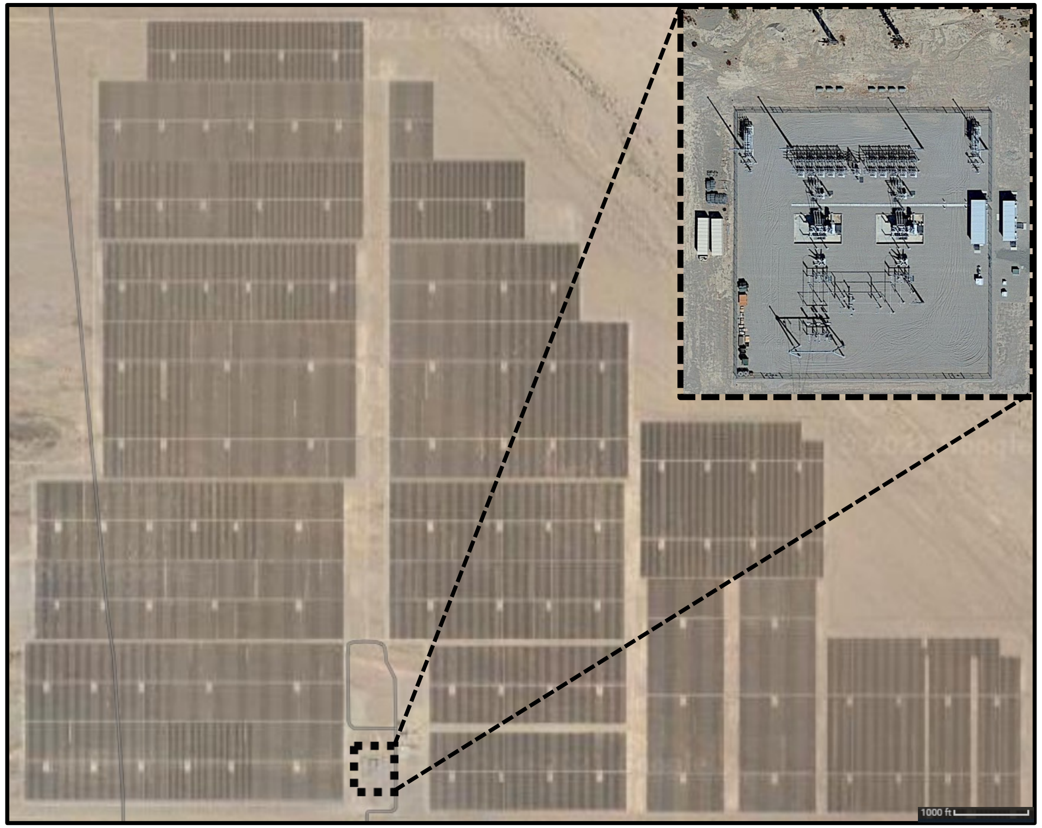
Spatial parallelization & separation

- **Fortran**
- **PSCAD (existing EMT tool)**

DAE – Differential Algebraic Equations

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)

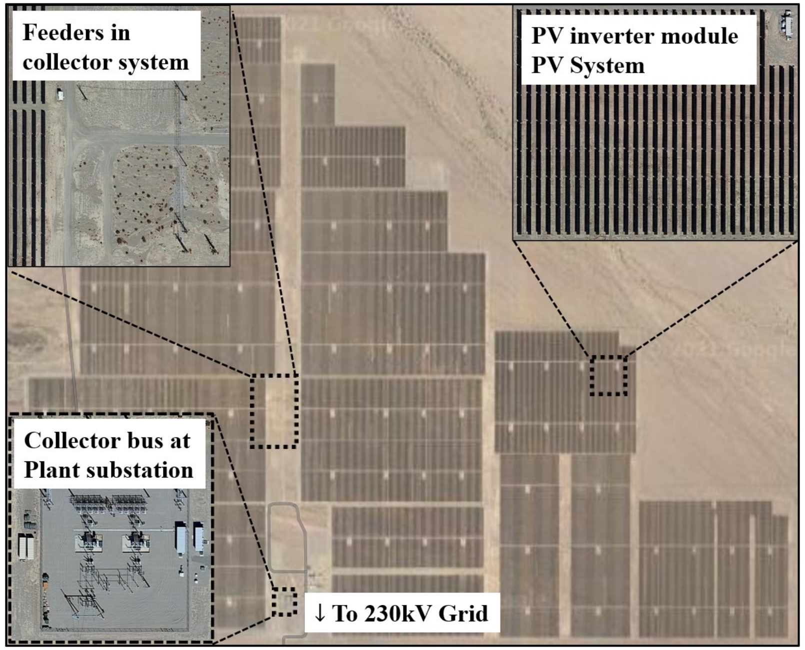
1. Collect data on PV plant components
2. Develop dynamic model of individual PV plant components
3. Test individual component model and iterate for accuracy
4. Develop distribution grid model of the PV plant
5. Test distribution grid model and iterate for accuracy
6. Integrate individual components in distribution grid model
7. Test and iterate

High-fidelity PV plant model development process

PV – Photovoltaic

High-Fidelity Switched System Model Simulations: Test Results from EMT Simulator/Fortran

High-Fidelity EMT Dynamic Model of PV Plant:



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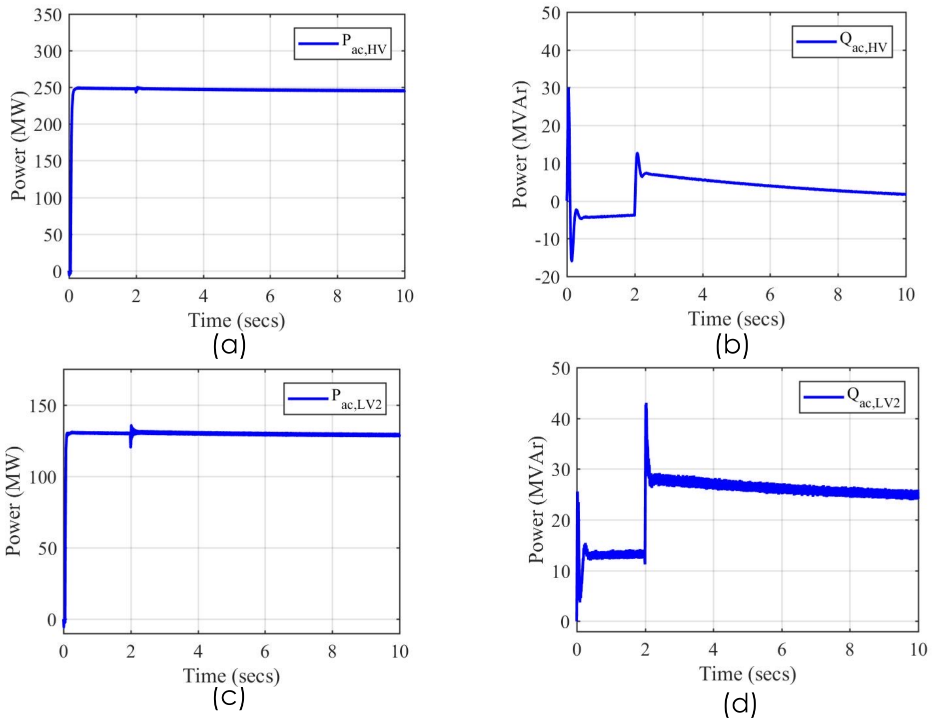
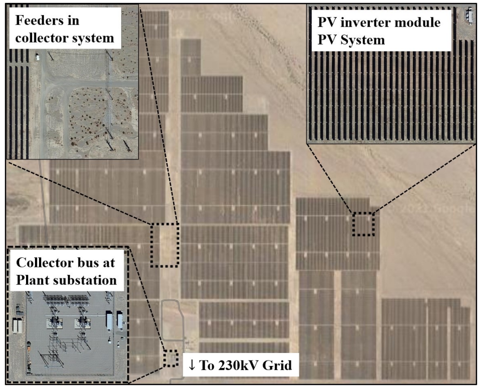


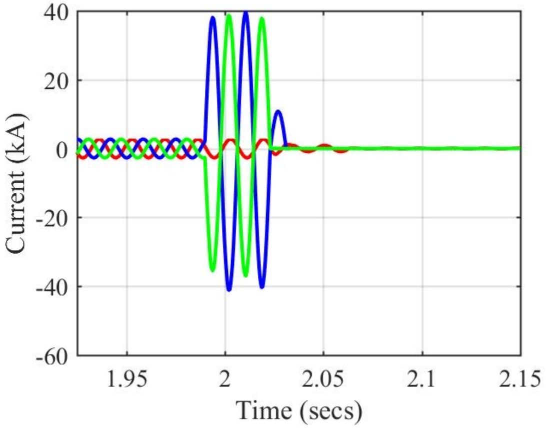
> 95% accuracy** observed (with events like capacitor switching), **up to 320x faster

EMT Grid-PV Plant Model Simulations: Test Results from EMT Simulator/Fortran

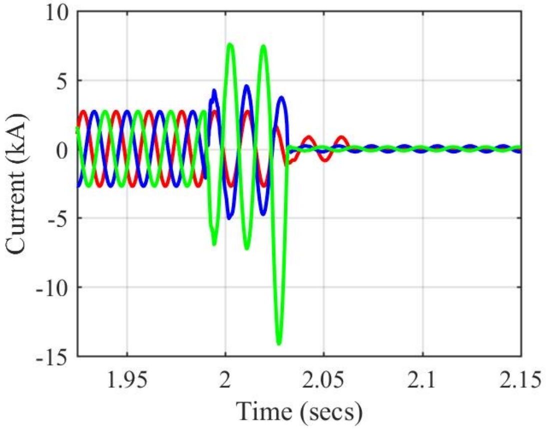


Specific PV plant-1 (One of the affected PV plants during Angeles Forest fire event)

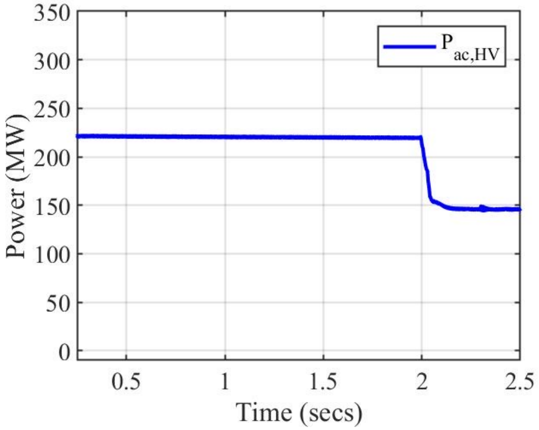
Courtesy: Google maps and NERC*



Local end (fault)



Remote end (fault)

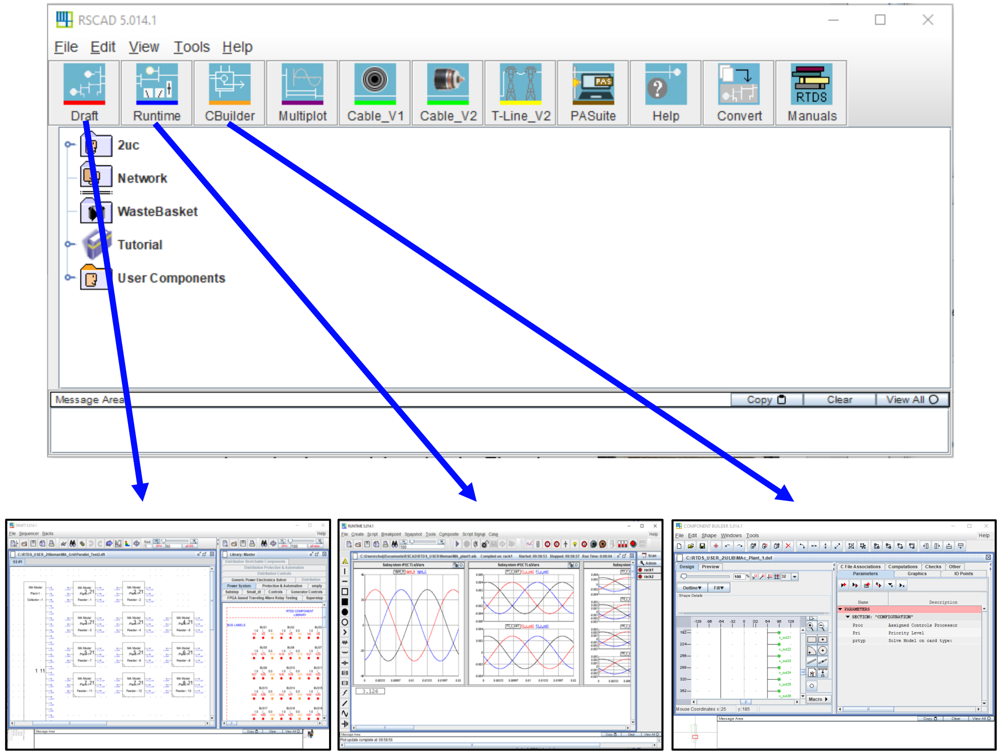


PV plant power output

Inverter trips and reduced power from PV plant as expected (along with ac grid measurements)

Hardware-based EMT Simulation – Software (RSCAD)

RSCAD



Simulated models in Draft

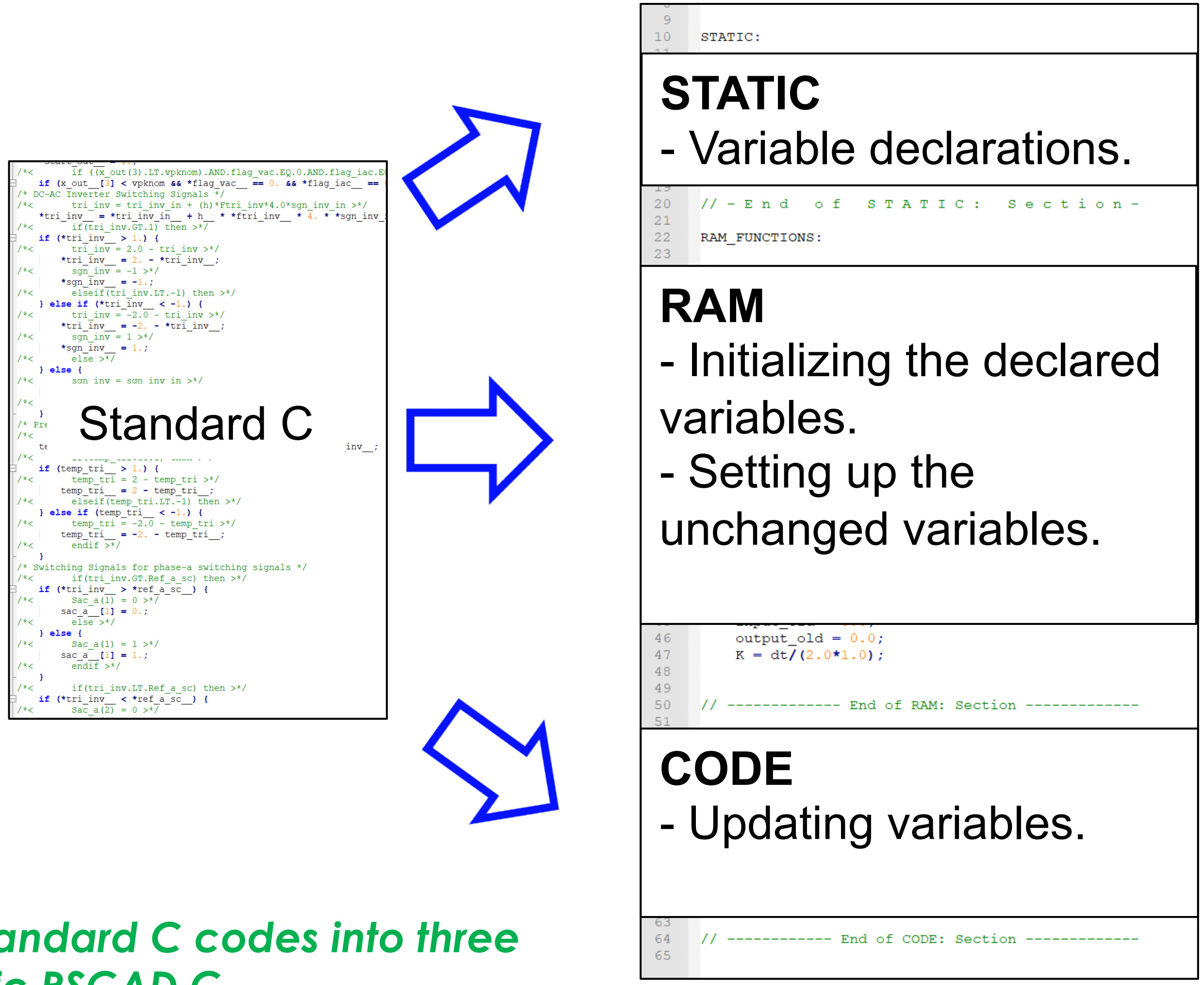
Plots in Runtime

Custom modeling in CBulider

- Software for Real-Time Digital Simulator (RTDS)
  - Draft
  - Runtime
  - CBuilder
  - Cable, T-line
- Custom modeling
  - Utilized to apply the numerical algorithms for the high-fidelity modeling in RSCAD.

Hardware-based EMT Simulation – Software (RSCAD)

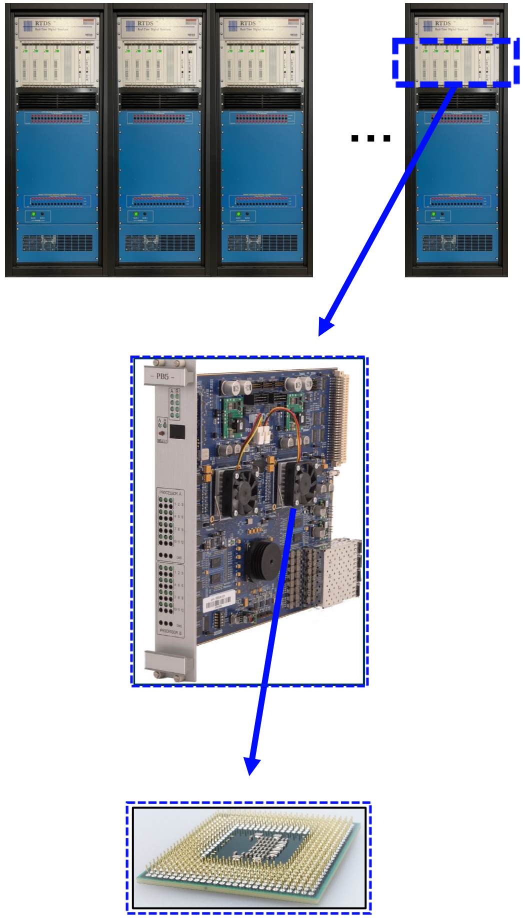
- Specific RSCAD C language for custom component modeling
  - **Different from standard C language.**
  - 3 Sections
    - **STATIC**
    - **RAM**
    - **CODE**
  - Needs
    - Optimized for hardware-based EMT simulation.
    - Understanding of three sections in the specific C in RSCAD.
    - Knowledge of EMT modeling/simulation.



Specific C in RSCAD

Optimizing and allocating the standard C codes into three sections in specific RSCAD C

Hardware-based EMT Simulation – Hardware (RTDS)



Racks

- Up to 60 Racks can be connected.

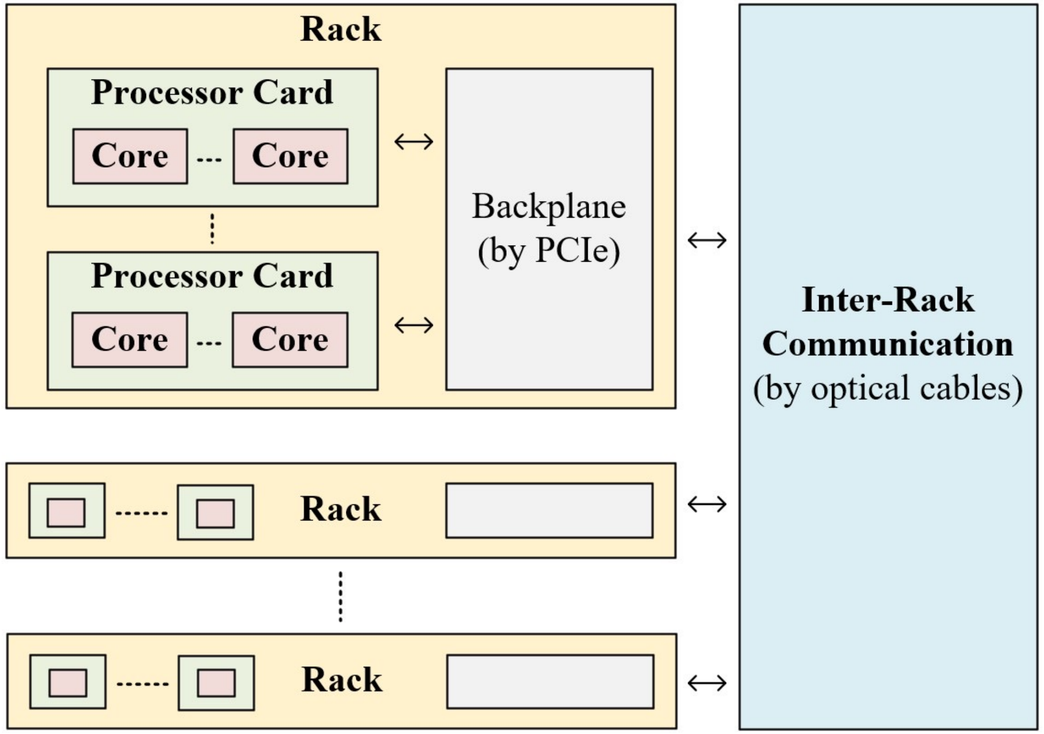
Processor Card

- up to 6 cards per Rack

Cores

- 2 cores per Card

Hardware structure of RTDS



Maximum capability – 60 Racks, 360 Cards, 720 Cores!

Challenges in Hardware-based EMT Simulation

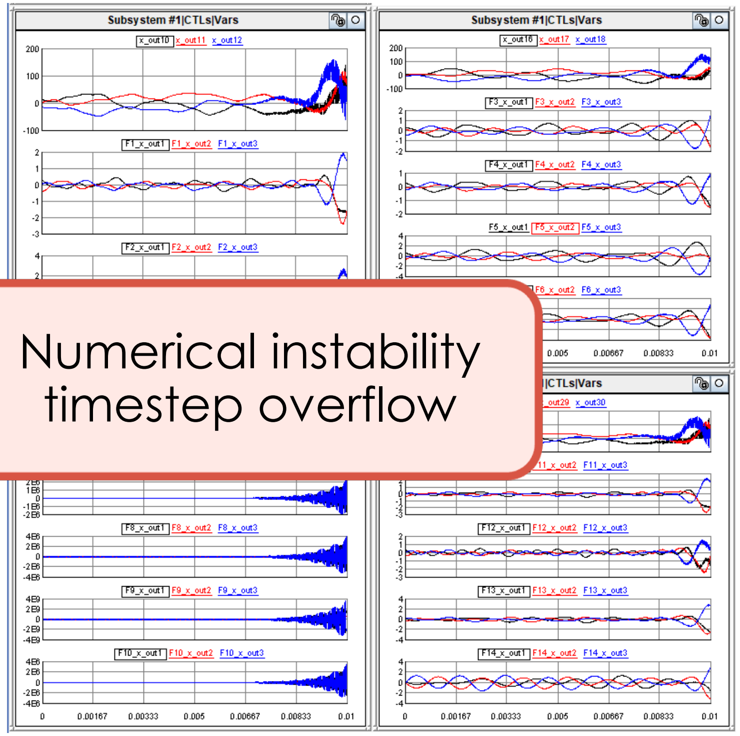
- Numerical instability in a single rack

Fixed simulation time-step

Fixed computing power

Large number of components

→ Long simulation time-step requirement → Numerical instability timestep overflow



Multi-racks implementation is required for large-scale EMT simulation!

Challenges in Hardware-based EMT Simulation

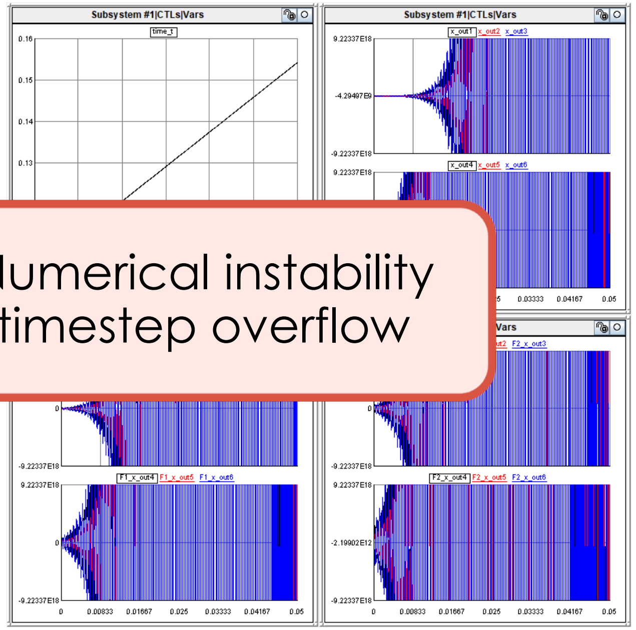
- Numerical instability in multi-racks

Timestep delay

Multiple racks

Large number of components

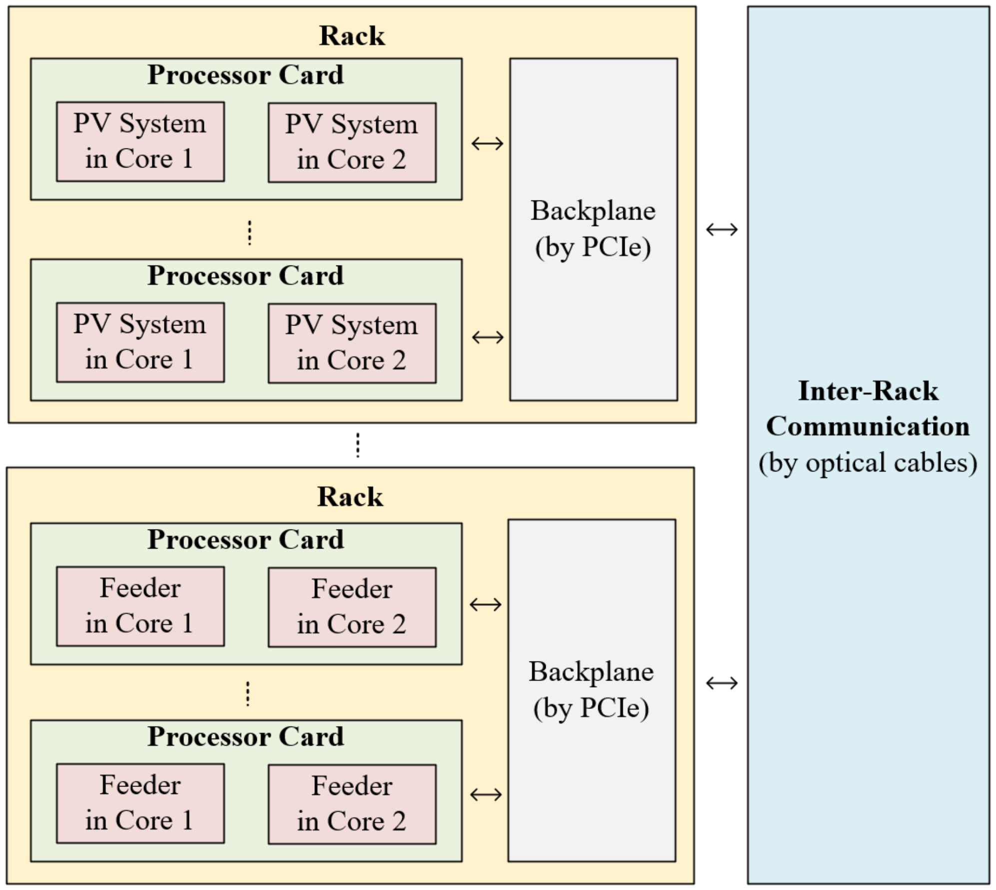
→ Multiple timestep delay → Numerical instability timestep overflow



Smaller simulation timestep is required with multi-rack implementation!

Techniques for Hardware-based EMT Simulation

- **Proposed techniques**
  - *Pseudo real-time implementation* with optimizing simulation time-step.
    - T_{sim} = 0.25 μs with T_{sol} = 100 μs.
  - *C script partitioning* in multiple cores.
    - PV systems, feeders.
  - *Equivalencing techniques* at boundaries of partitioning.
    - Inductors between feeders and collector bus.



T_{sim} - Simulation timestep (time interval to update the states in the system)
T_{sol} - Solution timestep (time interval to solve the system equations)

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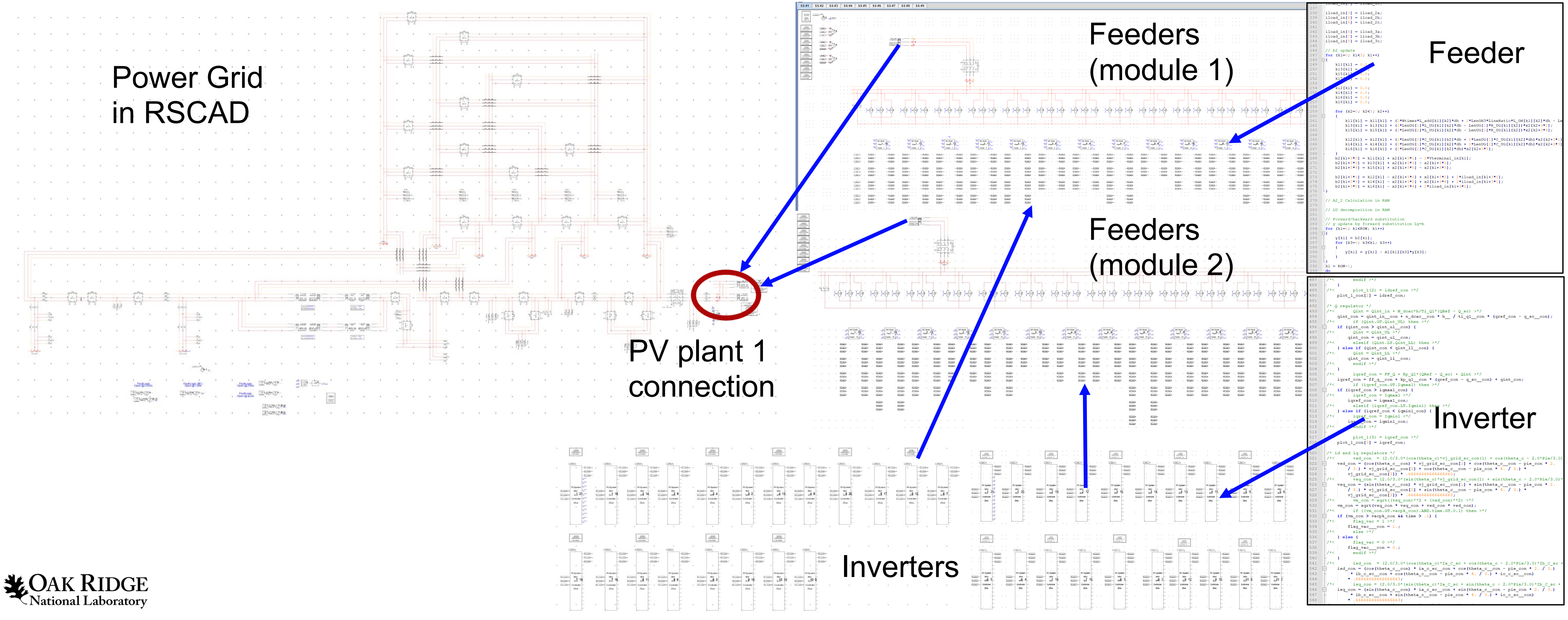
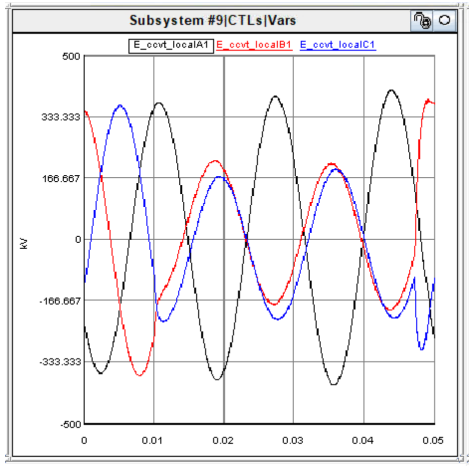
Hardware-based EMT Simulation in RTDS/RSCAD

- **A PV Plant with the power grid**
  - 8 racks (PV plant) + 1 rack (Power grid) – 9 racks in total, pseudo real-time

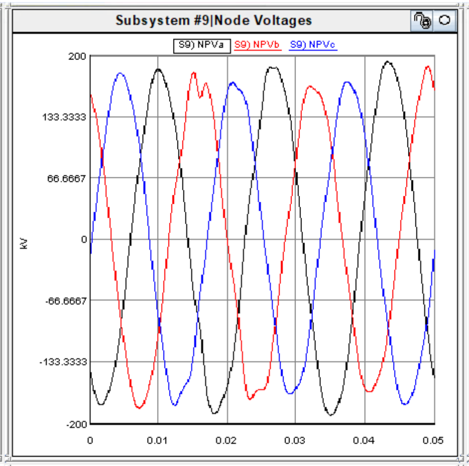


Validation of Hardware-based EMT Simulation Model

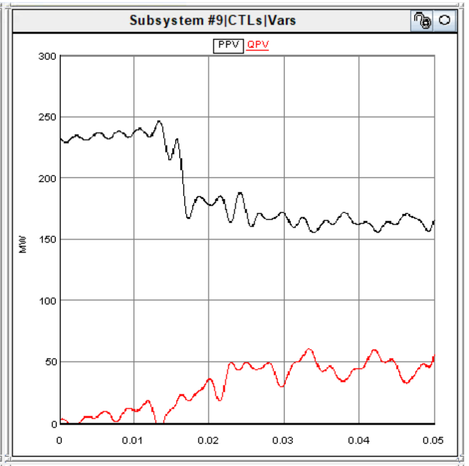
Voltages at faulted area



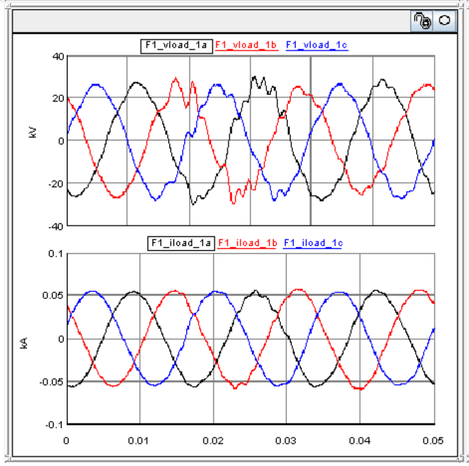
Voltages at plant terminal



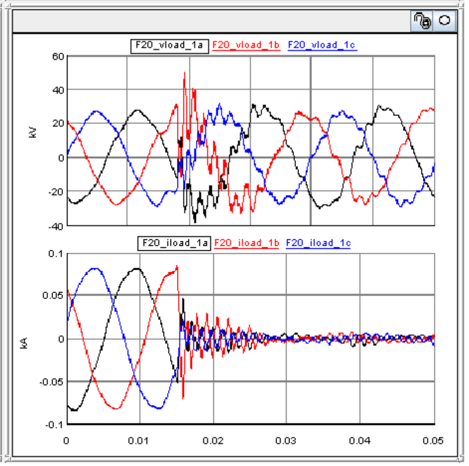
Active power from PV plant (Partial reduction)



Successful replication of the partial tripping of the PV plant during Angeles Forest Fire 2018!



Voltages and currents for the inverter going through the fault within the PV plant



Voltages and currents for tripped inverter within the PV plant

Lessons Learnt (if any)

- High-fidelity IBR modeling is required.
- Sensitive and accurate data for both the grid and IBR is required for accurate EMT simulations.
- Knowledge of both software and hardware are required for hardware-based EMT simulation for large-scale systems.
- Understanding of the limitations of software/hardware for EMT simulation optimization.

Impact

- Assist with post-event analysis
- Help in design and testing of protection systems
- More renewable energy integration
- Accurate reliability study for IBR for risk assessment and mitigation
- Help in power system planning with IBR

Gaps & Challenges Observed (Not Solved Yet)

- Scalability of EMT simulation needs to be addressed for large-scale EMT simulation.
- Parallel computing capability needs to be applied for large-scale EMT simulation.
- EMT simulation capability needs to be extended for large-scale DERs dominated-distribution grid (by short lines).