Library of Advanced dynamic Models of large-scale PV plants

Suman Debnath

Suman Debnath

PESI Group, EEID Division, ESTD

Team: Oak Ridge National Laboratory, Southern California Edison, Georgia Institute of Technology, Pennsylvania State University, California Independent System Operator, Southwest Power Pool, Oklahoma Gas & Electric

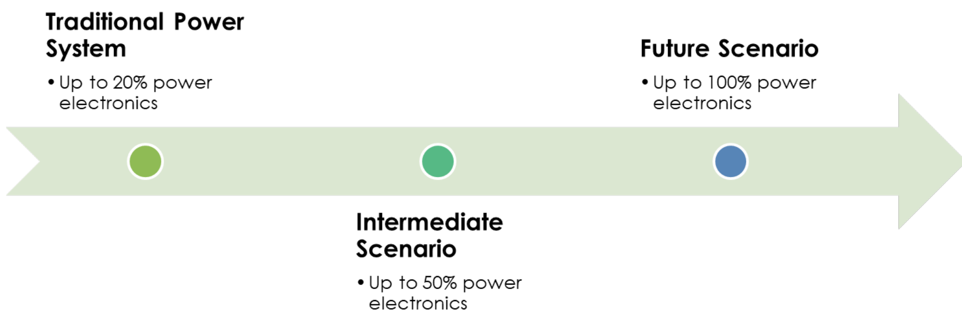
Outline

- Introduction to challenges with EMT and PV plant simulations
- Advanced simulation algorithms and dynamic EMT models

EMT – Electromagnetic Transient
PV – Photovoltaic

Introduction: PE Grid Simulation Challenges

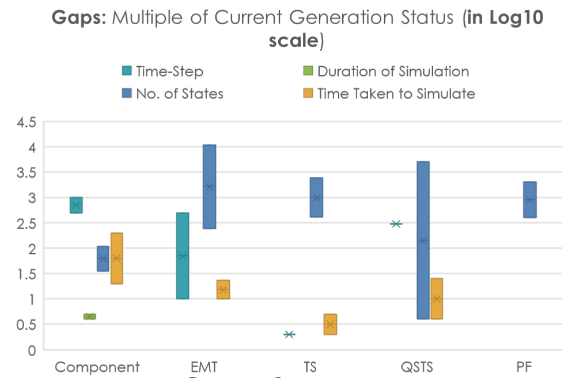
Penetration* of Power Electronics (PEs)



*Penetration defined by weighed average of power flowing through PEs

Power Electronics

- Inverter-based generations (eg, solar, wind)
- Power electronic loads (eg, electric vehicle chargers, extreme fast chargers, variable-frequency drives)
- Power flow controllers (eg, HVdc, FACTS)



Gaps Summary

Existing Simulators

- Largely for non-PE grids

Context for Gap Analysis

- Increased EMT studies performed for PE-grids
  - They are time-consuming (eg, ***3 hours for 20 s*** or ***2 hours for 30 s*** of simulation in small regions like AEMO, ERCOT)
- Do we need a new generation of simulators and advanced simulation algorithms?

More information may be found here: https://info.ornl.gov/sites/publications/Files/Pub141951.pdf.

HVdc – High Voltage Direct Current
FACTS – Flexible Alternating Current Transmission Systems
ERCOT – Electric Reliability Council of Texas
AEMO – Australian Energy Market Operator

PV Plant Simulation: Challenges

Inability of existing dynamic models of PV systems to predict behavior of grids under large disturbances

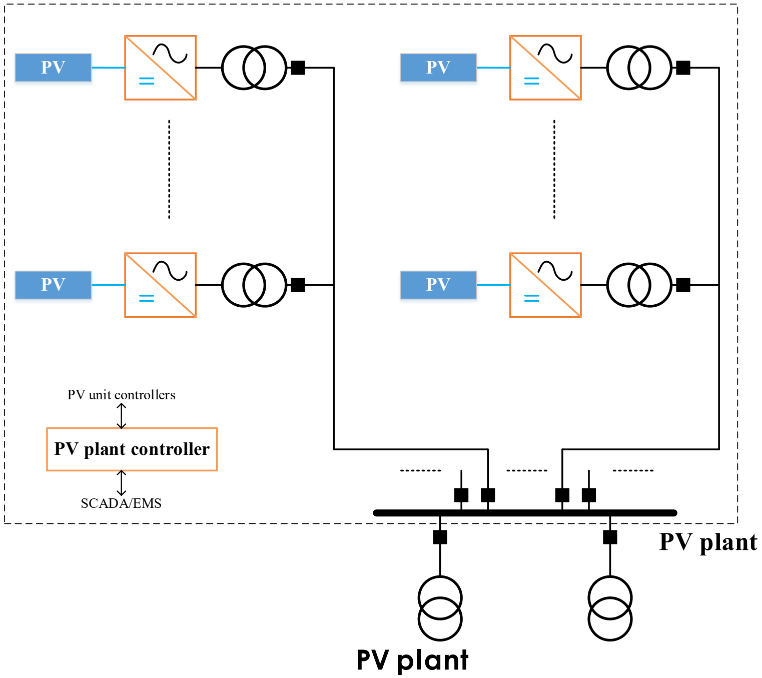
- E.g., unbalanced faults[1, 2, 3]

EMT models of PV systems can be time-consuming

- Extremely time-consuming to simulate ~ 500-1,000s inverters in 500 – 1,000 MW plants

EMT aggregated models

- Insufficient during momentary cessations or partial shutdowns observed

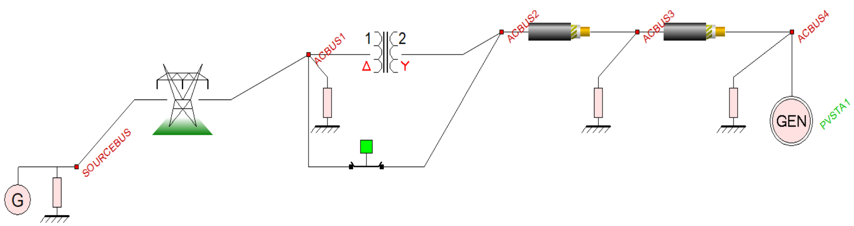


[1] North American Electric Reliability Corporation. *1200 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report*.
[2] North American Electric Reliability Corporation. *900 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report*.
[3] North American Electric Reliability Corporation. *April and May 2018 Fault Induced Solar Photovoltaic Resource Interruption Disturbances Report*.

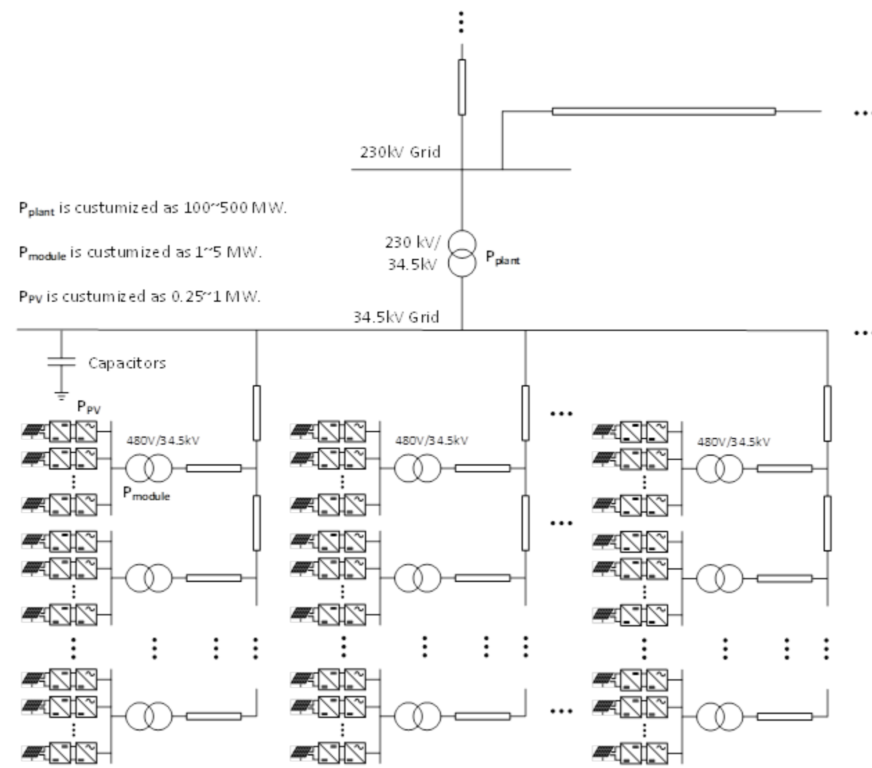
Simulation/Model Approaches: Overview

Library of dynamic models for PV systems

- High-fidelity model
- Quasi-dynamic model



Quasi-dynamic model



High-fidelity dynamic model

OAK RIDGE National Laboratory

OAK RIDGE National Laboratory

High-Fidelity Models

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

High-Voltage direct current (HVdc) Converter Substations with up to 2400 PE modules

- Modular Multilevel Converter (MMC)
- Alternate Arm Converter (AAC)
- Cascaded Two-Level (CTL) Converter

Multi-Terminal direct current (MTdc) Systems

- Up to 7 terminal MTdc system with 40 ac grid nodes in EMT

Electric Vehicle (EV) Chargers

- Distribution grid with EV charging stations (10s of inverters)
- Transmission-distribution grids with EV charging stations (100s of inverters, up to 500 nodes)
- Dynamic wireless charging systems

Large-Scale PV

- Distribution grid with PV (10s of inverters)
- PV plant (100s of inverters, up to 400 nodes)

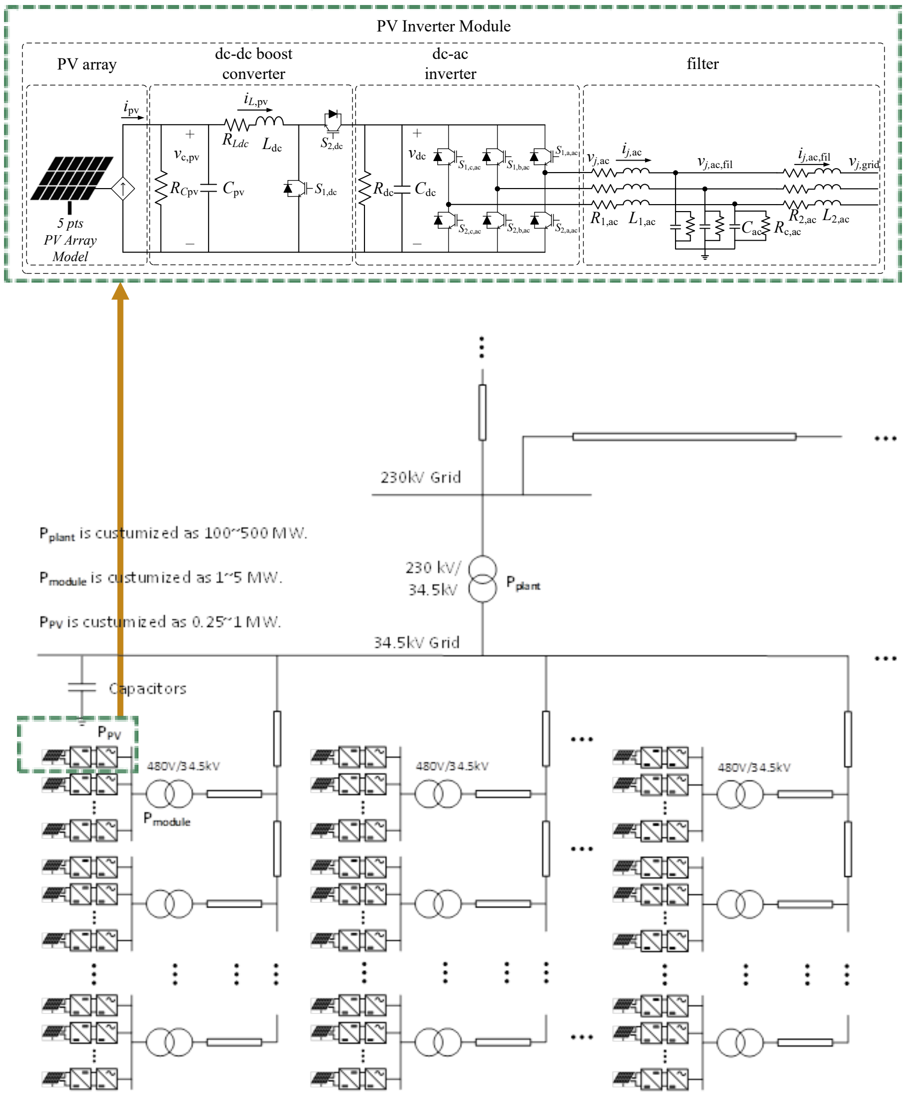
Multi-port PE Interfaces

- Multi-port autonomous reconfigurable solar power plant (MARS) with hybrid PV-energy storage system (ESS) with 1500 modules and 25 ac grid nodes in EMT

Lead: Suman Debnath
Contributors: Jingfan Sun, Phani Marthi, Jongchan Choi, Qianxue Xia, Shiyuan Yin, Shilpa Marti
DOE Programs Supported: EERE SETO, GMLC, OE TRAC, VTO XFC/LDRD

Outcome: Library of high-fidelity dynamic models in existing simulators (PSCAD) of large-scale PEs with advanced simulation algorithms with up to 17,000x speed-up observed

High-Fidelity Model: Model Description



PV plant

High-Fidelity Models

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

OAK RIDGE National Laboratory

High-Fidelity Model: Simulation Algorithms' Overview

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

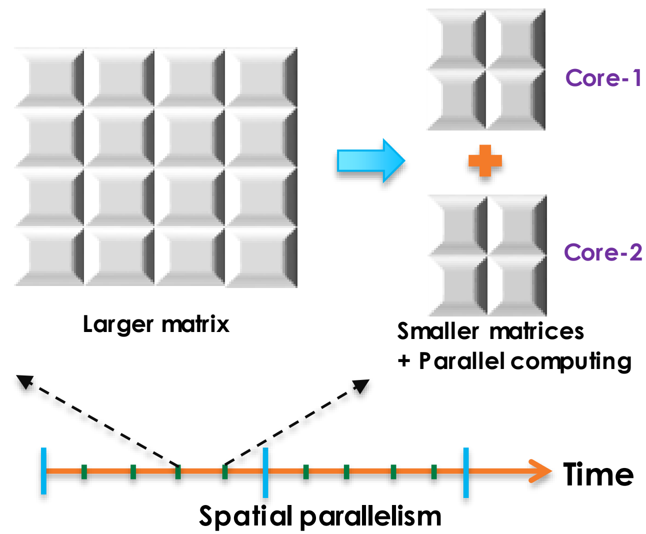
$$\dot{\mathbf{x}} = \mathbf{f}_2(\mathbf{x}, \mathbf{u}, t)$$

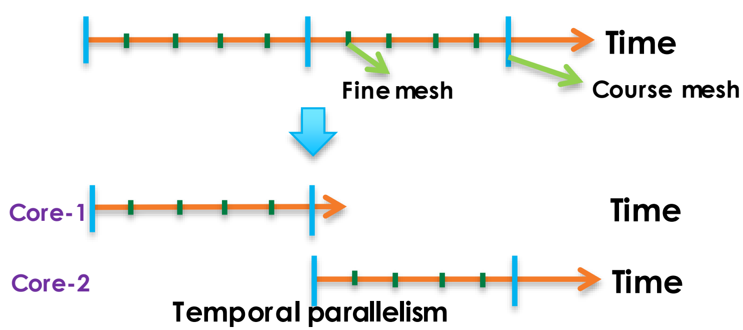
Combined DAEs for system model

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

Discretized and linearized system model using single discretization

- Spatial parallelization & separation
  - **Fortran**, C++, CUDA implementations (futuristic EMT-TS tool)
  - **PSCAD (existing EMT tool)**
- Time-parallel simulations
  - C++ implementations

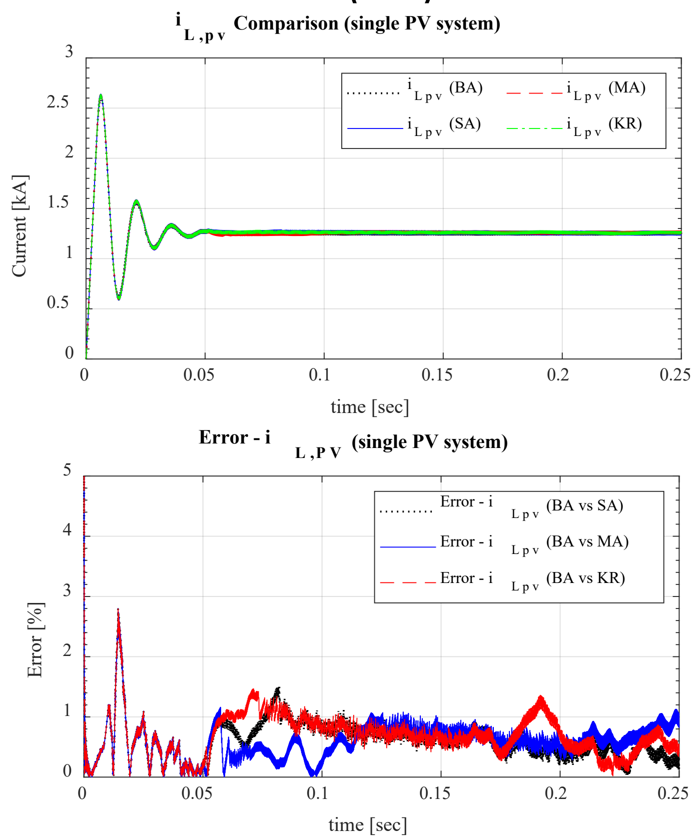




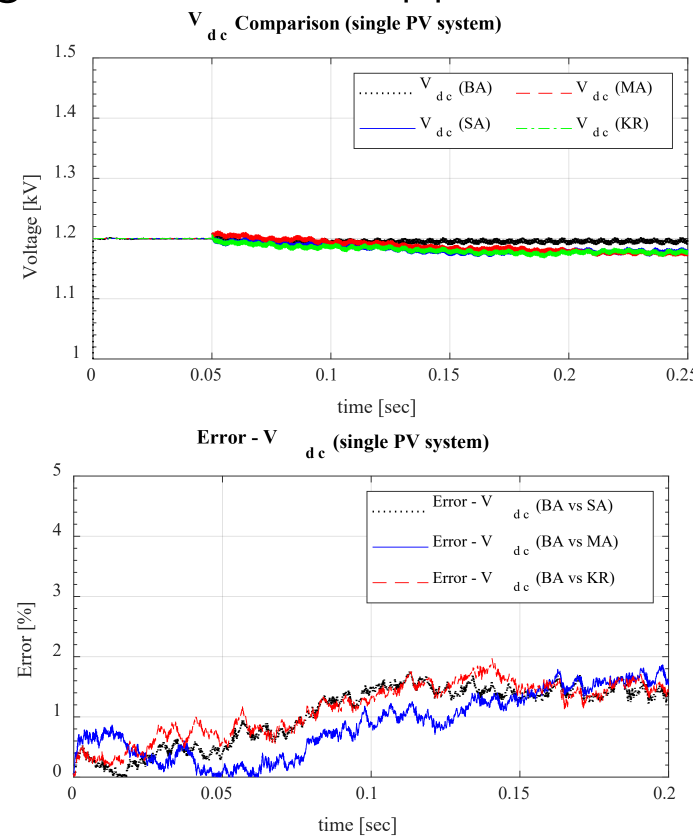
DAE – Differential Algebraic Equations

High-Fidelity Model: Simulation Results

- Baseline model (BA): PSCAD library components
- Single A-matrix (SA): No advanced algorithm
- Multiple A-matrix (MA): Advanced algorithm with approximation
- Kron's Reduction (KR): Advanced algorithm without approximation

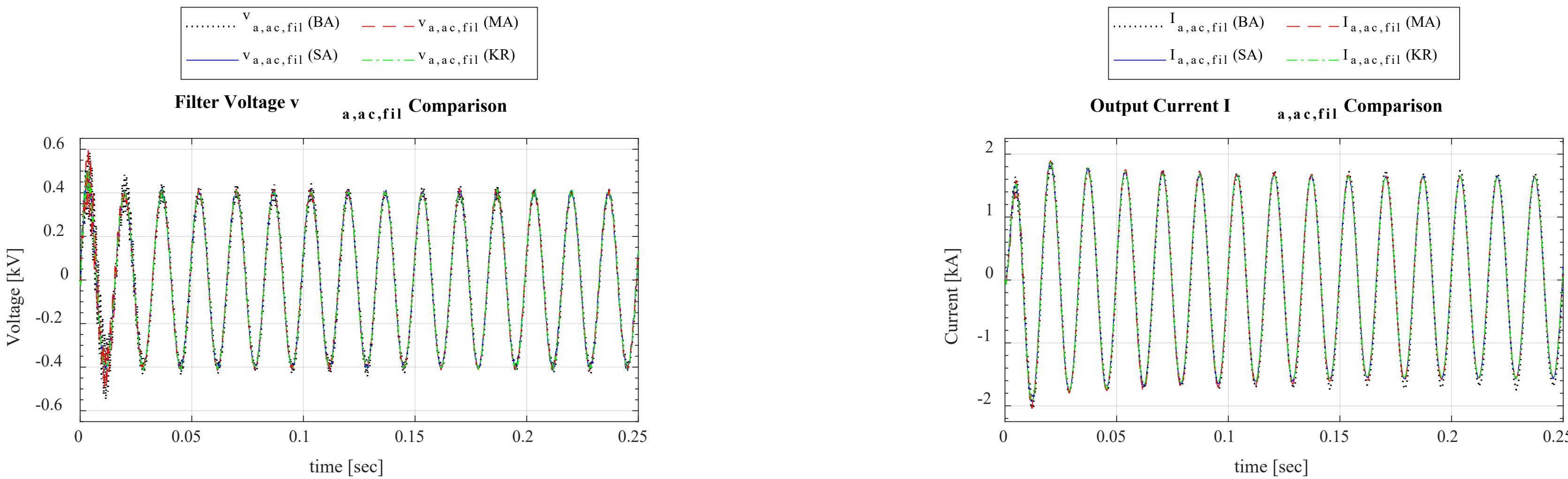


Inductor current (of dc-dc converter)

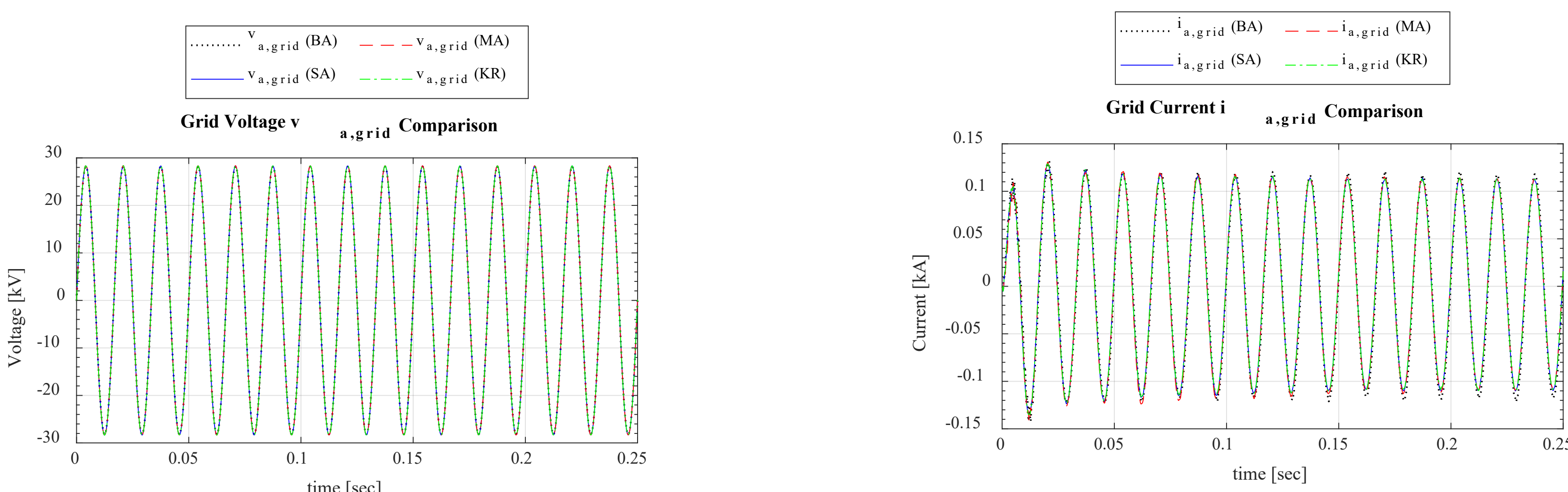


dc-link voltage (of ac-dc inverter)

High-Fidelity Model: Simulation Results



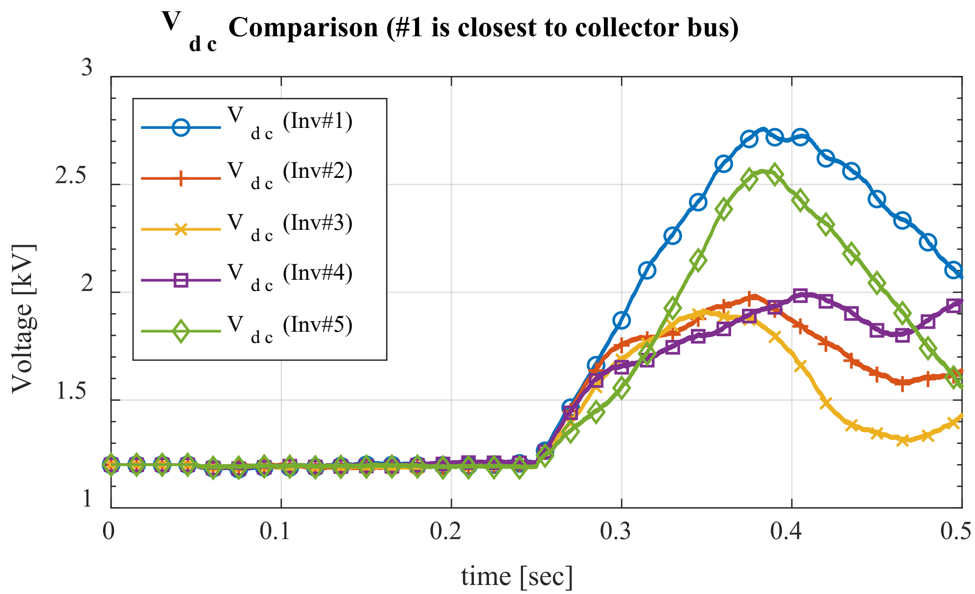
Filter voltage and output current (of ac-dc inverter)



Grid voltage and output current (of distribution transformer)

Up to 326x speed-up*, *less than 2% errors with the proposed simulation algorithm!

High-Fidelity Model: Simulation Results



Difference in the dc link voltage response observed in each individual inverter during faults

Need for high-fidelity dynamic models during design and planning phase – specially, to identify fault responses from individual inverters

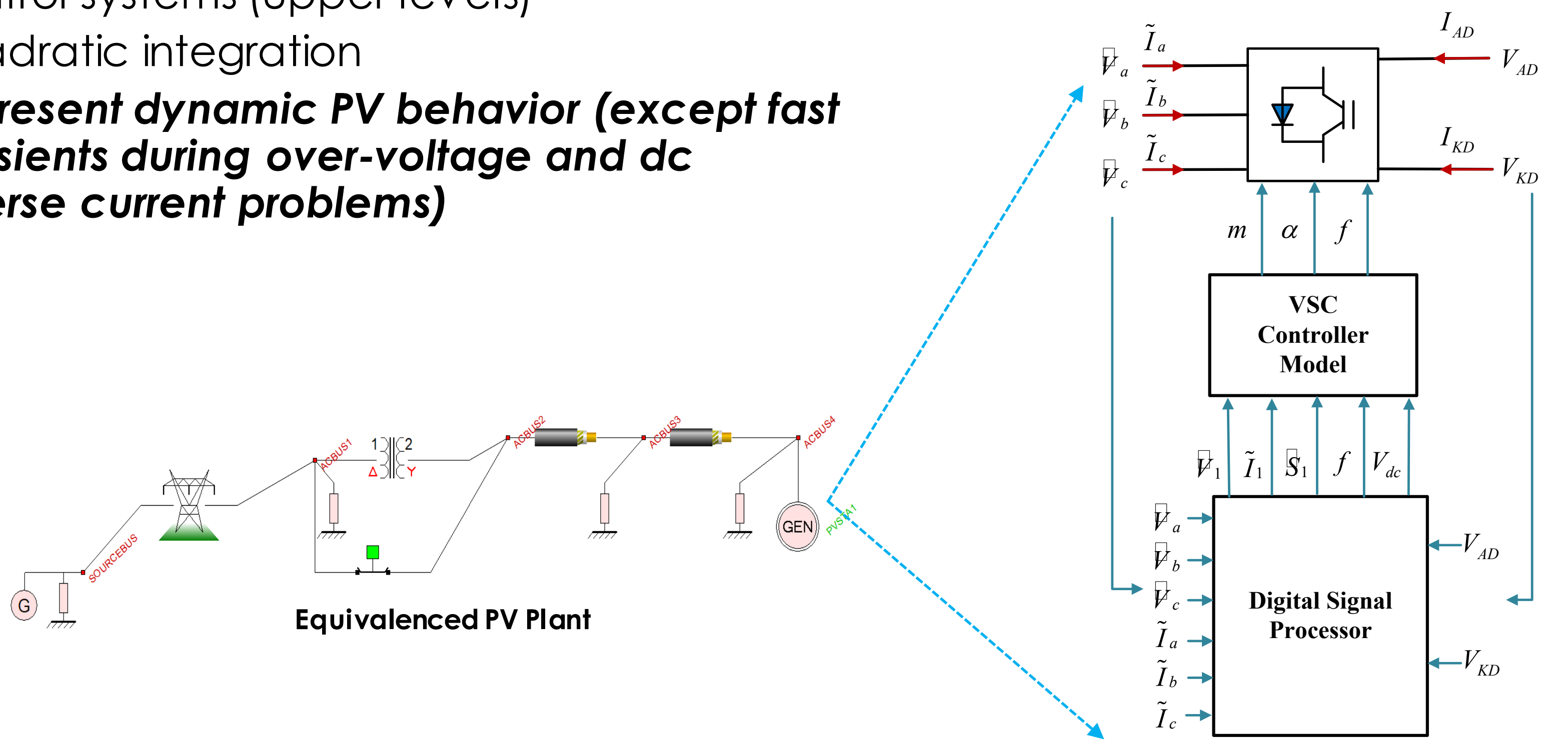
OAK RIDGE National Laboratory

Quasi-Dynamic Models

Quasi-Dynamic Model: Model Description

Quasi-Dynamic Models

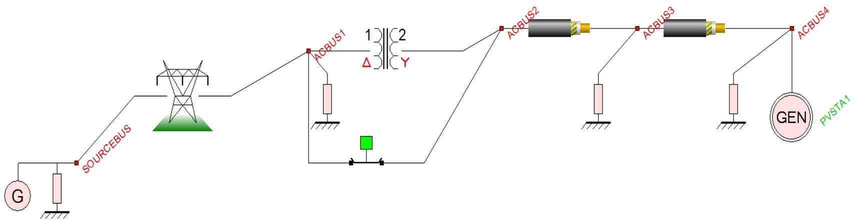
- Averaged electrical behavior
- Control systems (upper levels)
- Quadratic integration
- ***Represent dynamic PV behavior (except fast transients during over-voltage and dc reverse current problems)***

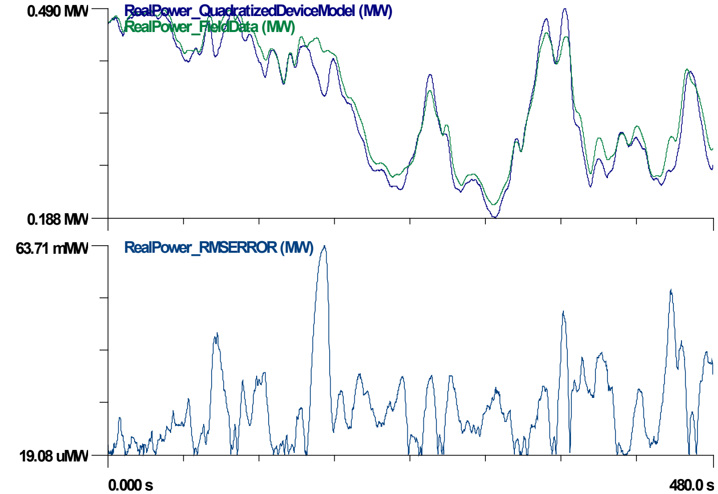


Equivalenced PV Plant

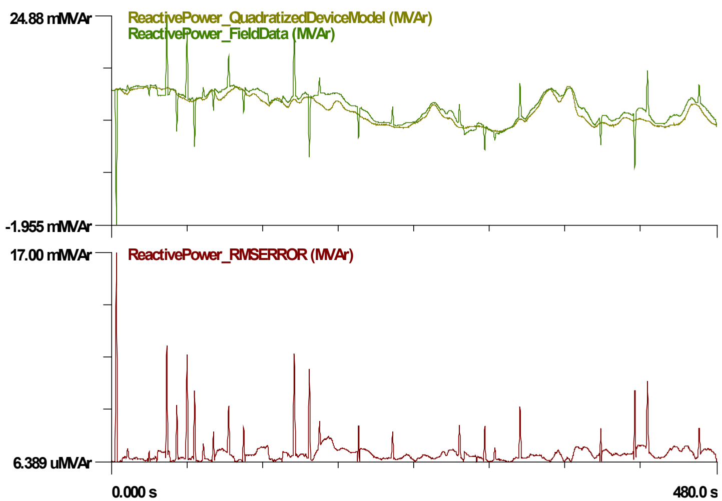
Quasi-Dynamic Model of PV Inverter

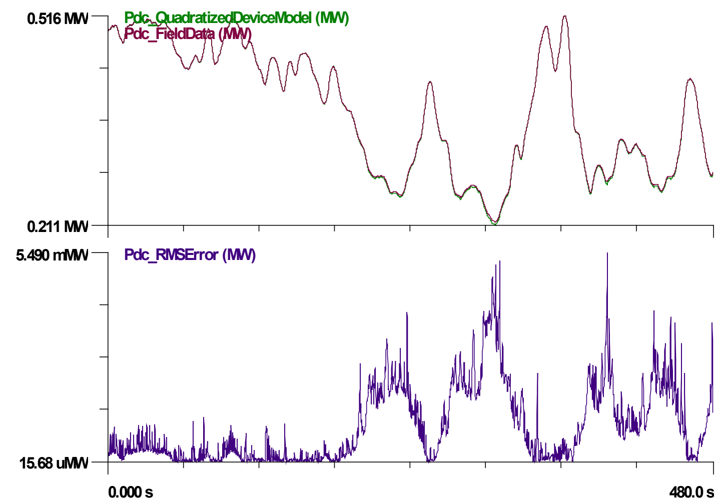
Quasi-Dynamic Model: Simulation Results





PV Plant





>95% accuracy in reactive power of quasi-dynamic model with respect to field data (average error < 5%)

>96% accuracy in ac and dc power of quasi-dynamic model with respect to field data (average error < 4%)

Up to 8200x speed-up*, *less than 5% errors with the proposed simulation algorithm!

Conclusions & Next Steps

- EMT PE-grid challenges introduced
- High-fidelity PV plant models for large-scale PV plants (with hundreds to thousands of inverters)
  - Up to 326x speed-up and less than 2% errors observed
- Quasi-dynamic model of small-scale PV plants and equivalenced large-scale PV plants
  - Up to 8200x speed-up and less than 5% errors observed
- Next-generation EMT capability (future)
  - Simulation algorithms and high-performance computing capability

References

- 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.
- K. Liu, A. P. Sakis Meliopoulos, O. Osamuyi, S. Cai, "Quasi-Dynamic Domain Modeling and Simulation of Voltage Source Converters", submitted to 2022 IEEE Innovative Smart Grid Technologies (ISGT) North America.
- S. Debnath, M. Elizondo, Y. Liu, P. R. Marthi, W. Du, S. Marti, Q. Huang, "High Penetration Power Electronics Grid: Modeling and Simulation Gap Analysis", Technical Report, August 2020. https://info.ornl.gov/sites/publications/Files/Pub141951.pdf.
- S. Debnath and M. Chinthavali, "Numerical stiffness based simulation of mixed transmission systems," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 12, pp. 9215-9224, Dec. 2018.

Acknowledgement

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under Solar Energy Technologies Office (SETO) Agreement Number 36532.

Contact Information:

Suman Debnath
debnaths@ornl.gov