Transient and dynamic simulations of large power systems with high levels of IBRs

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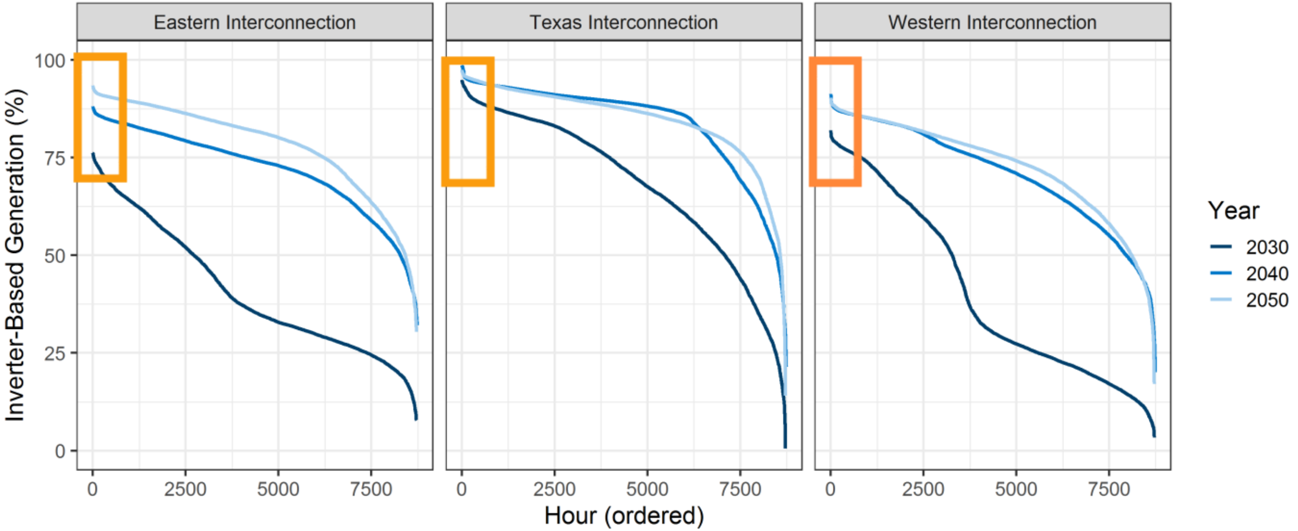
Content

Motivation

- Inverter-based resources (IBRs, including PV, wind, battery energy storage, and HVDC) are expected to be the main generation source in many regions.
- All major U.S. interconnections are expected to reach **peak instantaneous** IBR levels of **75-98%** within the lifespans of IBRs being installed today [1]:

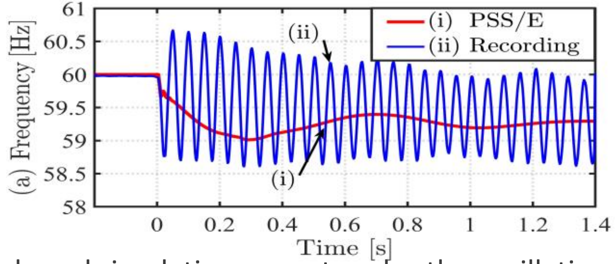


[1] Data from 2021 DOE/NREL Solar Futures Study: https://www.nrel.gov/analysis/solar-futures.html

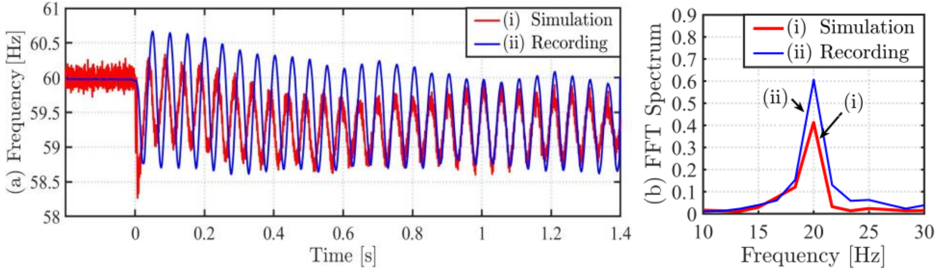
EMT simulation needs and challenges

- IBRs have **faster response and more complicated dynamics** than synchronous generators.
- Conventional phasor-domain simulators may fail to capture those dynamics
- **Electromagnetic transient** (EMT) simulations capture the fast dynamics, but **are extremely slow for large systems:**
  - ➢ **Circuit-based network**: *R-L-C*
  - ➢ **High dimensional network**: 3-phase
  - ➢ **High fidelity device models**: distributed line model, power electronics
  - ➢ **Small time step**: typically, 50 microsecond

19 Hz IBR-driven oscillation example:
11/21/2021 on Kauai, Hawaii;
Field data and EMT simulation [1]



phasor-based simulation cannot replay the oscillation event



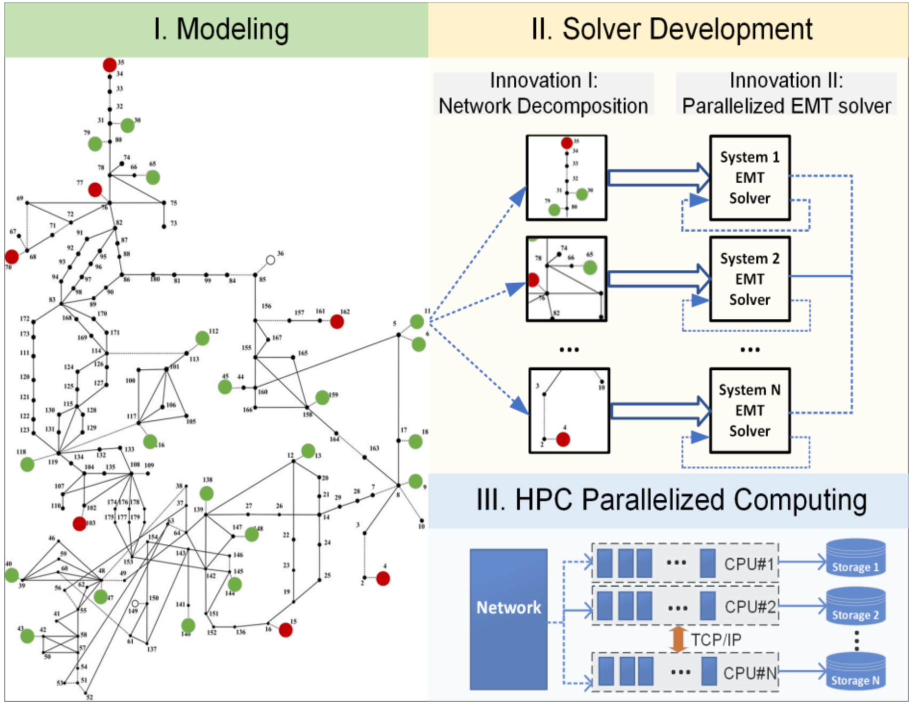
EMT simulation can replay the oscillation event

[1] S. Dong, et al., "Analysis of November 21, 2021, Kauaʻi Island Power System 18–20 Hz Oscillations," 2023, arXiv:2301.05781.

Introduction of ParaEMT: features

ParaEMT features [1]

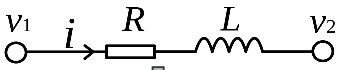
- Open source, Python-based EMT simulator
- Dynamic model library
  - ➢ Compatible with IEEE/CIGRE DLL standard
  - ➢ Generic IBR models
- Parallelizable network solution
  - ➢ Nodal formulation
  - ➢ Bordered block diagonal (BBD) based network solver
  - ➢ HPC-compatible
- Available test cases
  - ➢ 2-area, 9-bus, 39-bus, 179-bus, 240-bus
- Other features
  - ➢ Down sampling
  - ➢ Snapshot



[1] M. Xiong, B. Wang, D. Vaidhynathan, J. Maack, M. Reynolds, A. Hoke, K. Sun, D. Ramasubramanian, V. Verma, and J. Tan, "An Open-Source Parallel EMT Simulation Framework," Electric Power Syst. Res., June 2024.

EMT simulation framework in ParaEMT

Nodal formation for the network [1]

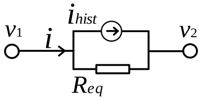


$$L\frac{di}{dt} = (v - Ri)$$

$$v = v_1 - v_2$$

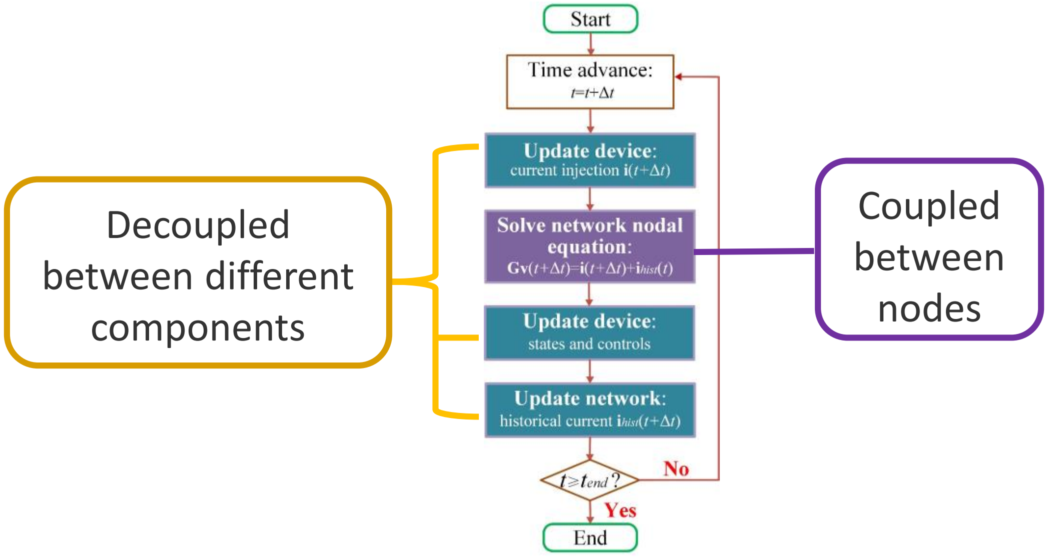
$$L\frac{i(t) - i(t-\Delta t)}{\Delta t} = \frac{v(t) + v(t-\Delta t)}{2} - R\frac{i(t) + i(t-\Delta t)}{2}$$

$$i(t) = \frac{v(t)}{R_{eq}} + i_{hist}(t-\Delta t)$$



$$\mathbf{G}\mathbf{v}(t) = \mathbf{i}(t) + \mathbf{i}_{hist}(t-\Delta t)$$

EMT simulation flowchart in ParaEMT

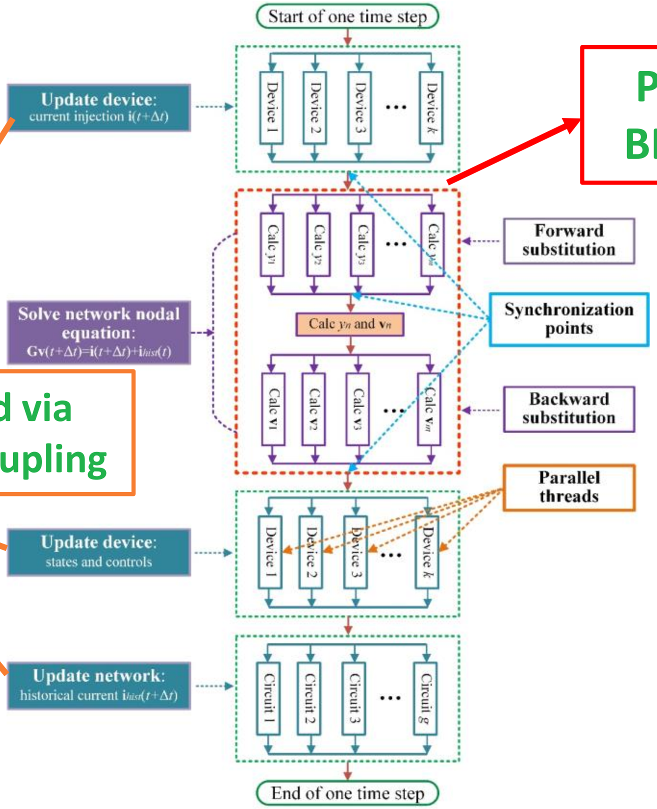


Disturbance models

- control reference step change;
- generator trip;
- state step perturbation;
- balanced/unbalanced bus faults;
- transmission line trip;
- load trip.

[1] H. W. Dommel, *EMTP Theory Book*. Portland, OR: Bonneville Power Admin., Aug. 1986.

Parallel EMT simulation strategy in ParaEMT



Parallelized via natural decoupling

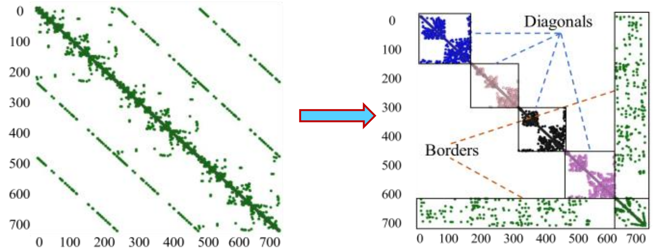
Parallelized via BBD method [1]

Bordered block diagonal (BBD) form

$$\mathbf{G} = \begin{bmatrix} \mathbf{G}_{11} & & & & \mathbf{G}_{1n} \\ & \mathbf{G}_{22} & & & \mathbf{G}_{2n} \\ & & \cdots & & \vdots \\ & & & \mathbf{G}_{mm} & \mathbf{G}_{mn} \\ \mathbf{G}_{n1} & \mathbf{G}_{n2} & \cdots & \mathbf{G}_{nm} & \mathbf{G}_{nn} \end{bmatrix}$$

$$\mathbf{G} = \mathbf{LU} = \begin{bmatrix} \mathbf{L}_{11} & & & & \\ & \mathbf{L}_{22} & & & \\ & & \cdots & & \\ & & & \mathbf{L}_{mm} & \\ \mathbf{L}_{n1} & \mathbf{L}_{n2} & \cdots & \mathbf{L}_{nm} & \mathbf{L}_{nn} \end{bmatrix} \begin{bmatrix} \mathbf{U}_{11} & & & & \mathbf{U}_{1n} \\ & \mathbf{U}_{22} & & & \mathbf{U}_{2n} \\ & & \cdots & & \vdots \\ & & & \mathbf{U}_{mm} & \mathbf{U}_{mn} \\ & & & & \mathbf{U}_{nn} \end{bmatrix}$$

$$\mathbf{LUv} = \mathbf{i} + \mathbf{i}_{hist}$$



A BBD form of the WECC 240-bus system

[1] S. Fan, H. Ding, A. Kariyamasam, A. M. Gole, "Parallel electromagnetic transients simulation with shared memory architecture computers," *IEEE Trans. Power Del.*, Jun. 2018.

Process of running an EMT simulation using ParaEMT

Load system data → **Solve power flow** → **Initialize the simulation** → **Run simulation** → **Save and plot results**

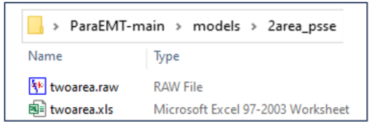
support PSS/E files

convert to 3-phase

online/offline plotting

Preparation:

1. Establish the PSSE `raw` file of a system
2. Define the `xls` format dynamic data
3. Put the above files under 'ParaEMT/models'



→

Step 0: Run and save power flow

- Set working folder
- Load the `raw` file
- Solve the power flow
- Save power flow data as a `json` file

→

Step 1: Initialize the simulation and run time domain simulation

- Simulation settings
- Initialize the simulation
- Time domain simulation
- Save results as a `pkl` file

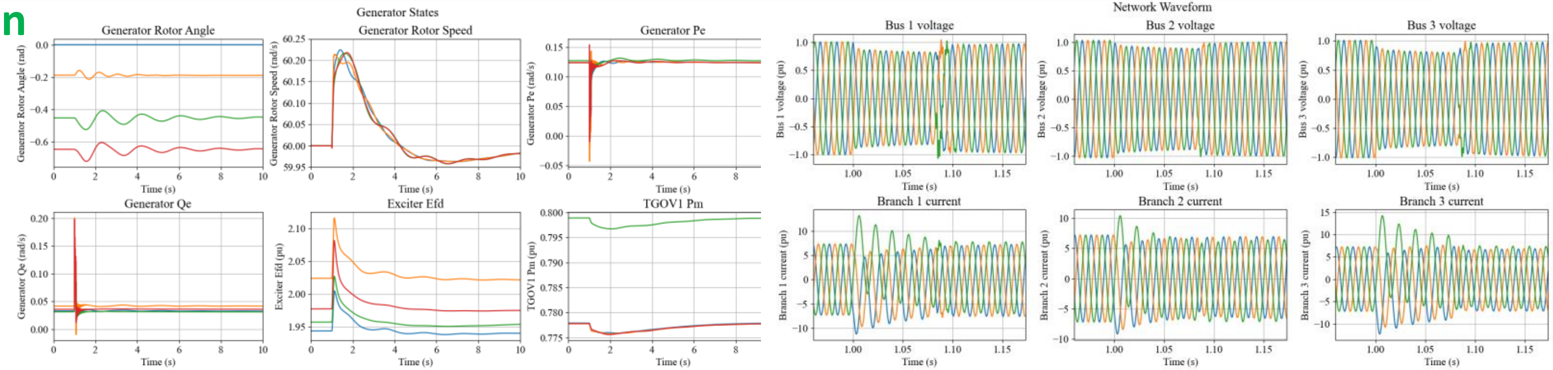
→

Step 2: Export the simulation results as `csv` files

- Load the saved `pkl` file
- Save the data to `csv` files
- Saved `csv` files

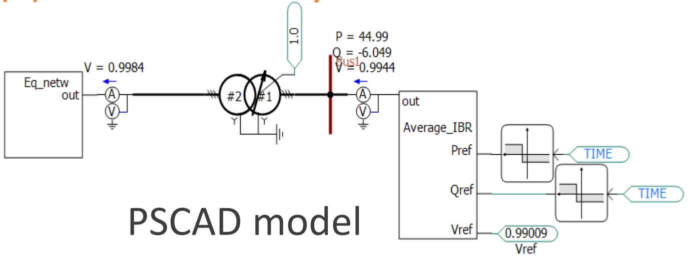
Plot the saved results for visualization

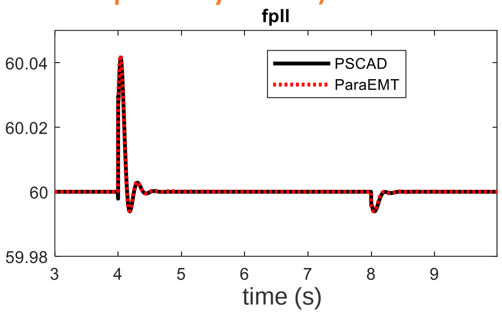
Visualization

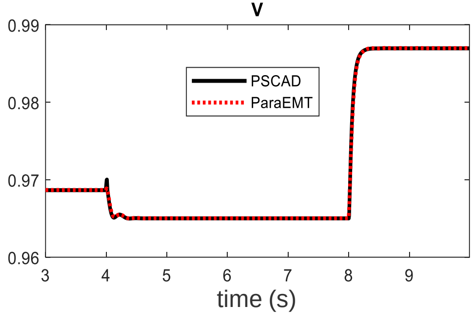


Accuracy validation against commercial tools

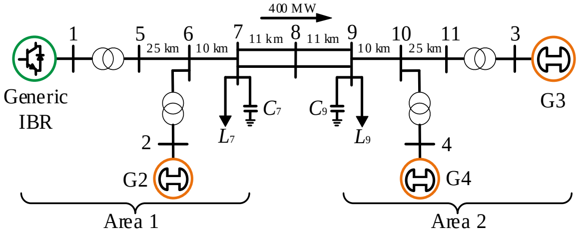
(1) Two machine system with a DLL IBR model (developed by EPRI)

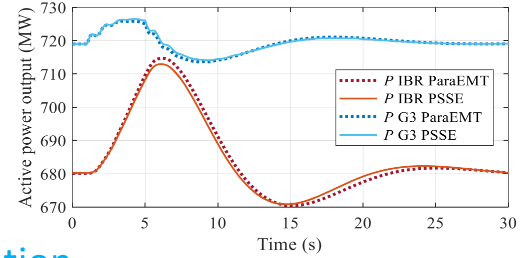


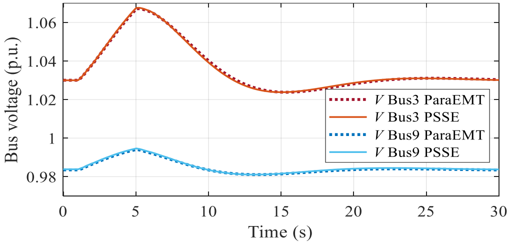




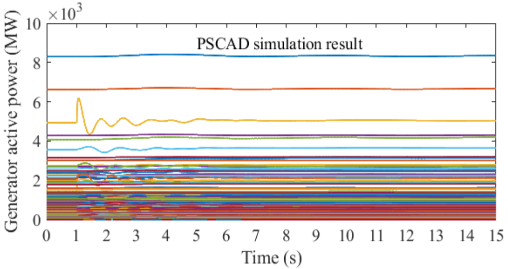
(2) Two-area system with all build-in models

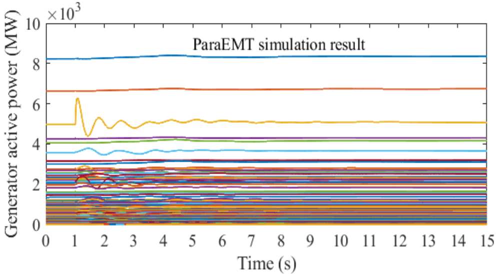






(3) 240-bus WECC system with 20% IBR penetration





Performance

(1) Performance on the 240-Bus WECC system

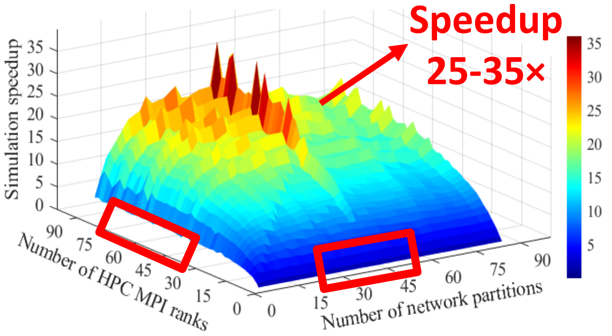
Time cost for a 1-s simulation with a 50-µs time step

Simulator	1 processor core No parallelization	8 processor cores Parallelization
PSCAD [1]	90 s	15 s
ParaEMT	29 s	28 s

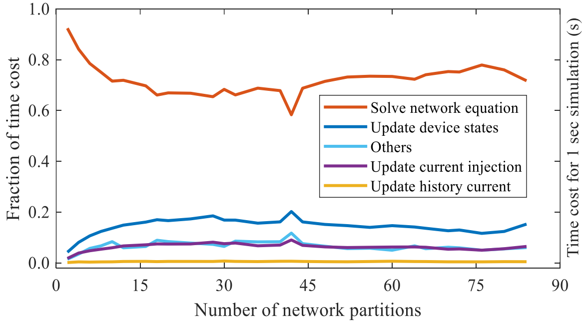
ParaEMT is efficient under series simulation

system size is no large enough to benefit from the BBD technique

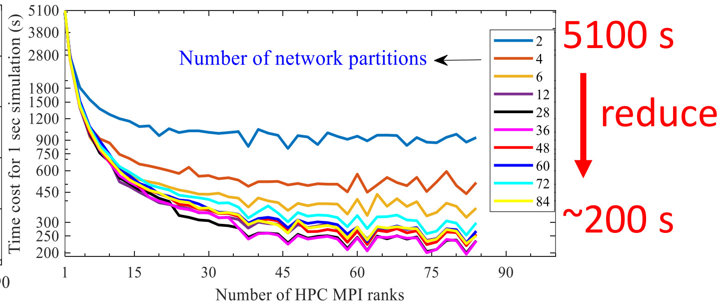
(2) Performance on a synthetic 10,024-Bus system



Speedup performance



Time cost fraction of sub-tasks

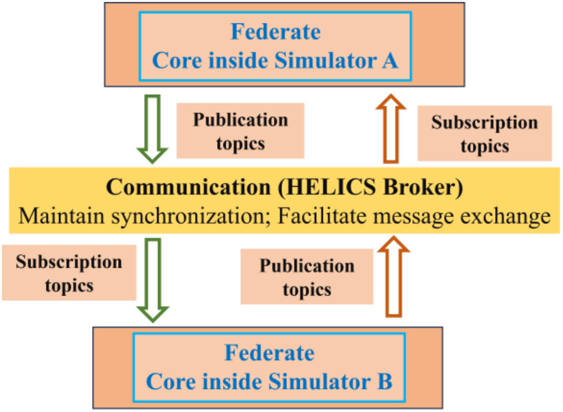


Time cost for a 1-s simulation

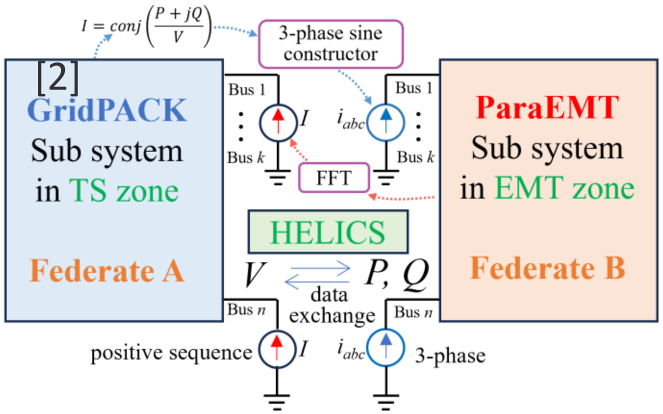
[1] B. Wang, R. W. Kenyon, J. Tan, "Developing a PSCAD Model of the Reduced 240-Bus WECC Test System," *2022 KPEC*.

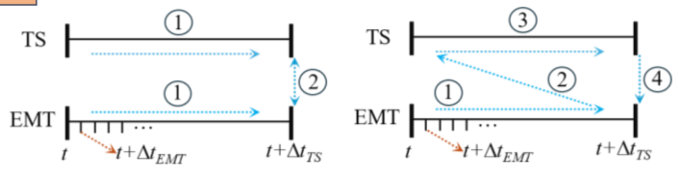
Hybrid simulation: ParaEMT + GridPACK via HELICS

HELICS co-simulation framework [1]



Hybrid simulation platform





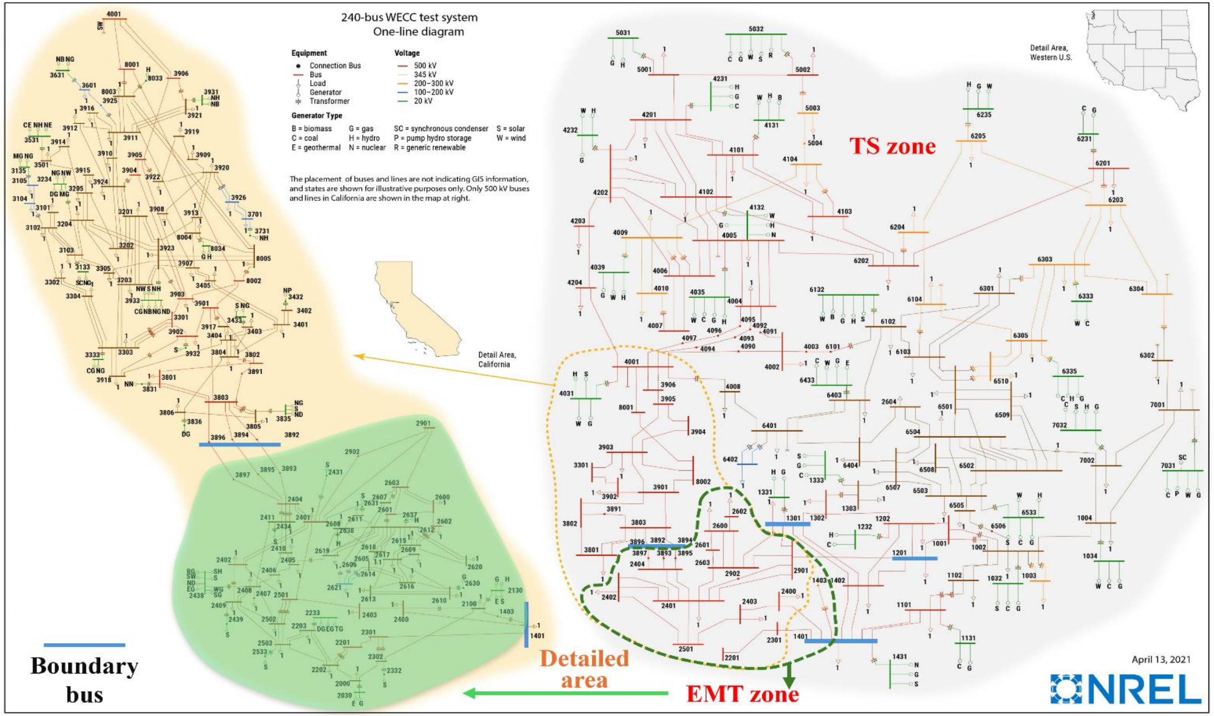
(a) Parallel interaction protocol (b) Serial interaction protocol

Typical EMT-TS hybrid simulation protocols [3]

[1] "Hierarchical Engine for Large-scale Infrastructure Co-Simulation (HELICS)," [Online]. Available: https://helics.org/.
[2] S. Abhyankar, R. Huang, S. Jin, B. Palmer, W. Perkins, Y. Che, "Implicit-integration dynamics simulation with the GridPACK framework," IEEE PES GM, 2021.
[3] D. Shu, et al., "A novel interfacing technique for distributed hybrid simulations combining EMT and transient stability models," IEEE Trans. Power Del., 2018.

System partitioning

One line diagram of the 240-bus WECC system partitioned into EMT and TS zones (simplified outside California region)



[1] M. Sajjadi, T. Xia, M. Xiong, K. Sun, A. Hoke, B. Wang, J. Tan, "A Participation Factor-based Approach for Defining the EMT Model Boundary for Power System Simulations with Inverter-Based Resources," *IEEE IECON conference*, 2024.

Design of simulation cases

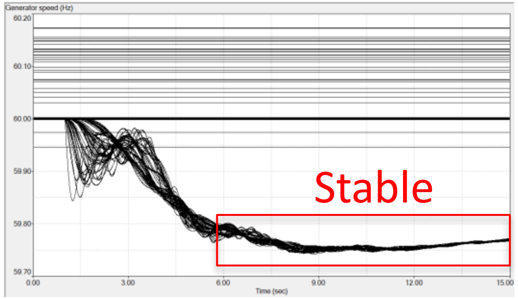
- A **4.6 Hz mode** is originated from the IBR Q/V control loop, where the proportional gain *Kp* [1] has a large influence on its stability.
- Varying *Kp* from 7 to 22 and simulating a generator trip event (2030-G).
- Two cases are selected where in case 2, EMT simulation is not stable while phasor domain simulation is stable.

Kp	10	11	12	13	14	15	16	17	18	19	20	21	22
TSAT													
ParaEMT													

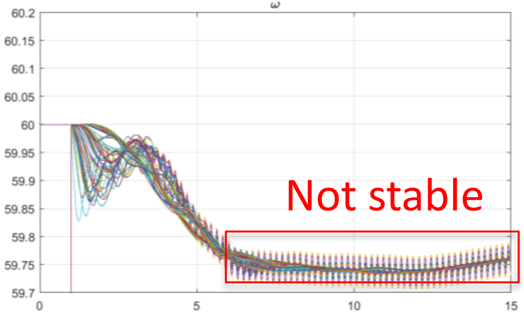
Case 1: Base case with *Kp*=7

Case 2: Marginally stable/unstable case with *Kp*=17

Generator speed by TSAT



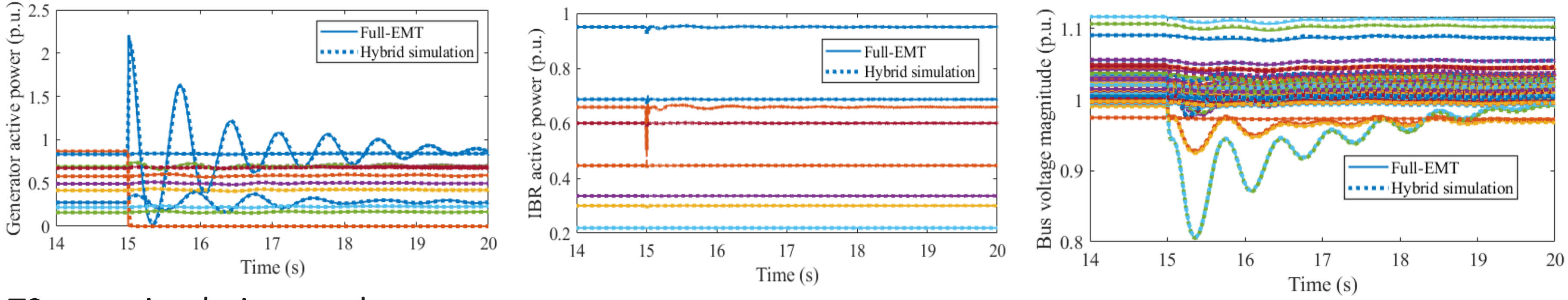
Generator speed by ParaEMT



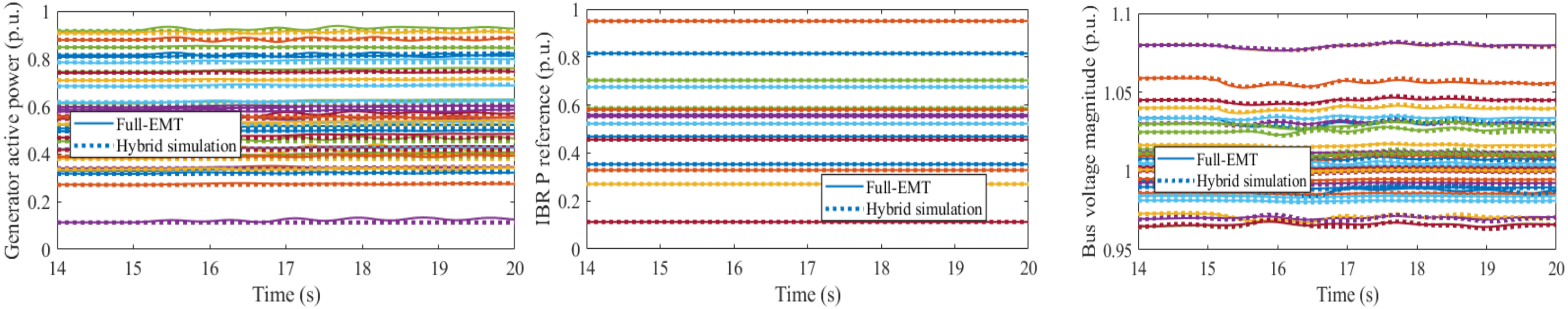
[1] P. Pourbeik, "Model User Guide for Generic Renewable Energy System Models," Elect. Power Res. Inst., Palo Alto, CA, USA, Tech. Rep. EPRI 3002006525, 2015.

Simulating slow electromechanical dynamics

EMT zone simulation results



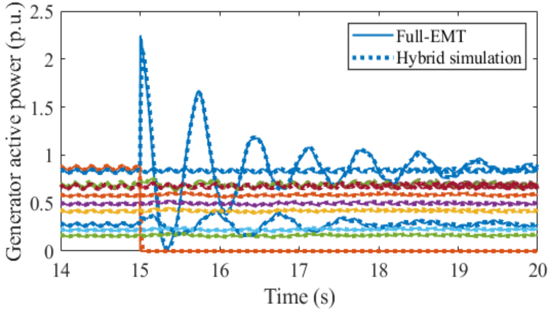
TS zone simulation results

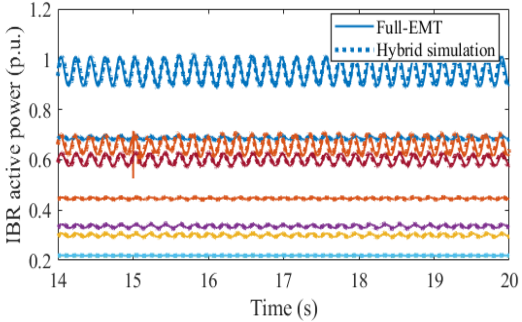


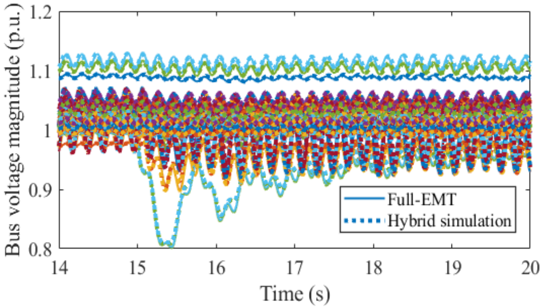
[1] M. Xiong, B. Wang, D. Vaidhynathan, J. Maack, Y. Liu, S. Abhyankar, B. Palmer, R. H. Auba, A. Hoke, K. Sun, V. Vittal, M. Sajjadi, M. Khamees, K. Huang, D. Ramasubramanian, V. Verma, M. Reynolds, and J. Tan, "EMT-TS Hybrid Simulation for Large Power Grids Considering IBR-Driven Dynamics," IEEE IECON, 2024.

Simulating IBR control-induced fast dynamics

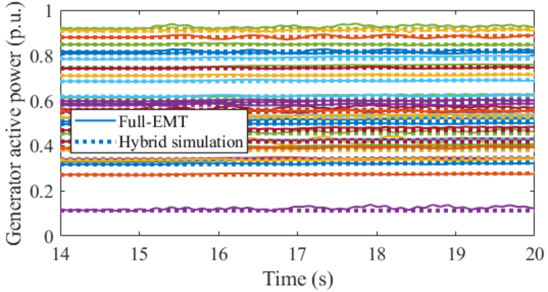
EMT zone simulation results

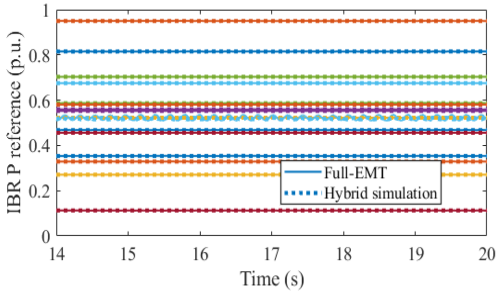


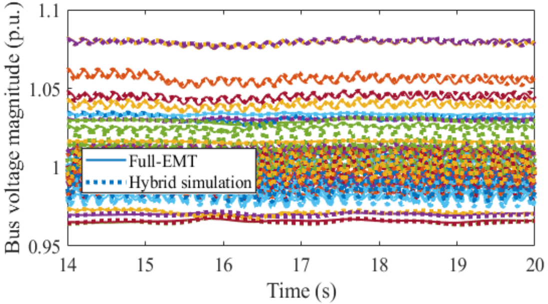




TS zone simulation results







Time Costs for a 1-Second Simulation

Tool	Full-EMT	EMT-phasor hybrid
PSCAD	90 s	/
ParaEMT	38.5 s	16 s

Hybrid-simulation provides a 2.4x speedup relative to ParaEMT

Lessons learned and questions

Modeling & Simulation:

- IBR modeling : detailed model? generic model? or both?
- System-wide EMT simulation for interconnection study at the planning stage.
- Replay, simulate, and analyze real-world IBR-induced oscillation events.
- Matching power flow can be a challenge between EMT and phasor.

Platform & Approach:

- An open-source platform for exploring and testing new EMT simulation algorithms and techniques (HPC, Cloud computing, GPU).
- Intelligent system partitioning approaches for hybrid simulation boundary determination.

Ongoing actions and future work

Remark:

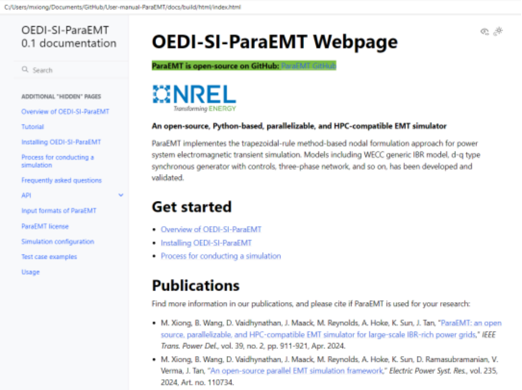
ParaEMT → Message Passing Interface (MPI) technology / Distributed memory parallelization paradigm

- Multiple compute nodes of an HPC system
- Multiple computers on a transmission control protocol (TCP) network
- A multi-core machine

→ Not limited to HPC systems

Ongoing work:

- ✓ OEDI-SI-ParaEMT
- ✓ User manual webpage
- ✓ Docker container
- ✓ GitHub maintenance



C:/Users/mxiong/Documents/GitHub/User-manual-ParaEMT/docs/build/html/index.html

OEDI-SI-ParaEMT 0.1 documentation

Search

ADDITIONAL "HIDDEN" PAGES

Overview of OEDI-SI-ParaEMT
Tutorial
Installing OEDI-SI-ParaEMT
Process for conducting a simulation
Frequently asked questions
API
Input formats of ParaEMT
ParaEMT license
Simulation configuration
Test case examples
Usage

OEDI-SI-ParaEMT Webpage

ParaEMT is open-source on GitHub: ParaEMT GitHub

NREL Transforming ENERGY

An open-source, Python-based, parallelizable, and HPC-compatible EMT simulator

ParaEMT implementes the trapezoidal-rule method-based nodal formulation approach for power system electromagnetic transient simulation. Models including WECC generic IBR model, d-q type synchronous generator with controls, three-phase network, and so on, has been developed and validated.

Get started

- Overview of OEDI-SI-ParaEMT
- Installing OEDI-SI-ParaEMT
- Process for conducting a simulation

Publications

Find more information in our publications, and please cite if ParaEMT is used for your research:

- M. Xiong, B. Wang, D. Vaidhynathan, J. Maack, M. Reynolds, A. Hoke, K. Sun, J. Tan, "ParaEMT: an open source, parallelizable, and HPC-compatible EMT simulator for large-scale IBR-rich power grids," *IEEE Trans. Power Del.*, vol. 39, no. 2, pp. 911-921, Apr. 2024.
- M. Xiong, B. Wang, D. Vaidhynathan, J. Maack, M. Reynolds, A. Hoke, K. Sun, D. Ramasubramanian, V. Verma, J. Tan, "An open-source parallel EMT simulation framework," *Electric Power Syst. Res.*, vol. 235, 2024, Art. no. 110734.

Future work:

- ➢ Additional dynamic models
- ➢ Compatibility with systems in various data formats
- ➢ Interface with other open-source and commercial tools
- ➢ GPU/cloud-based EMT simulation

ParaEMT GitHub Repository: http://github.com/NREL/ParaEMT_public
Test Case Repository for High Renewable Study: https://www.nrel.gov/grid/test-case-repository.html

Further information

Software and test cases

[1] B. Wang, J. Maack, D. Vaidhynathan, J. Tan, M. Reynolds, "Parallelizable Large-Scale Power System Electro-Magnetic Transient Simulator," NREL SWR-22-16, Dec. 2021.
[2] ParaEMT GitHub repository: http://github.com/NREL/ParaEMT_public
[3] Test Case Repository for High Renewable Study: https://www.nrel.gov/grid/test-case-repository.html

Related publications

[1] M. Xiong, B. Wang, D. Vaidhynathan, J. Maack, M. Reynolds, A. Hoke, K. Sun, and J. Tan, "ParaEMT: An Open Source, Parallelizable, and HPC-Compatible EMT Simulator for Large-Scale IBR-Rich Power Grids," *IEEE Trans. on Power Del.*, April 2024.
[2] M. Xiong, B. Wang, D. Vaidhynathan, J. Maack, M. Reynolds, A. Hoke, K. Sun, D. Ramasubramanian, V. Verma, and J. Tan, "An Open-Source Parallel EMT Simulation Framework," *Electric Power Syst. Res.*, June 2024.
[3] M. Xiong, B. Wang, D. Vaidhynathan, J. Maack, Y. Liu, S. Abhyankar, B. Palmer, R. H. Auba, A. Hoke, K. Sun, V. Vittal, M. Sajjadi, M. Khamees, K. Huang, D. Ramasubramanian, V. Verma, M. Reynolds, and J. Tan, "EMT-TS Hybrid Simulation for Large Power Grids Considering IBR-Driven Dynamics," *IEEE IECON*, 2024.
[4] M. Xiong, B. Wang, D. Vaidhynathan, J. Maack, R. H. Auba, Y. Liu, S. Abhyankar, B. Palmer, K. Sun, M. Sajjadi, M. Khamees, J. Tan, D. Ramasubramanian, V. Verma, V. Vittal, and A. Hoke, "Final Technical Report: Intelligently Partitioned Phasor-EMT Hybrid Simulations of Large-Scale, High-IBR Power Systems," *NREL/TP-5D00-89823*, 2024 (Forthcoming).
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Thank you!

Comments? Questions? Collaborations?

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