

Future Role of Hybrid Simulations in Assessing the Dynamic Stability of IBR Dominated Power Systems

Rick Wallace Kenyon, PhD



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Fall Technical Workshop

Brief Wallace History

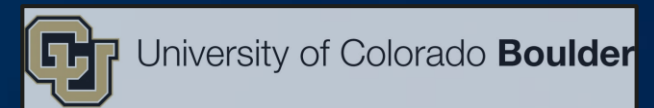
NREL 2017 - 2022:

- Coupled T&D simulations
- Electro-magnetic (EMT) modeling of the Maui power system

PhD at University of Colorado, Boulder 2022:

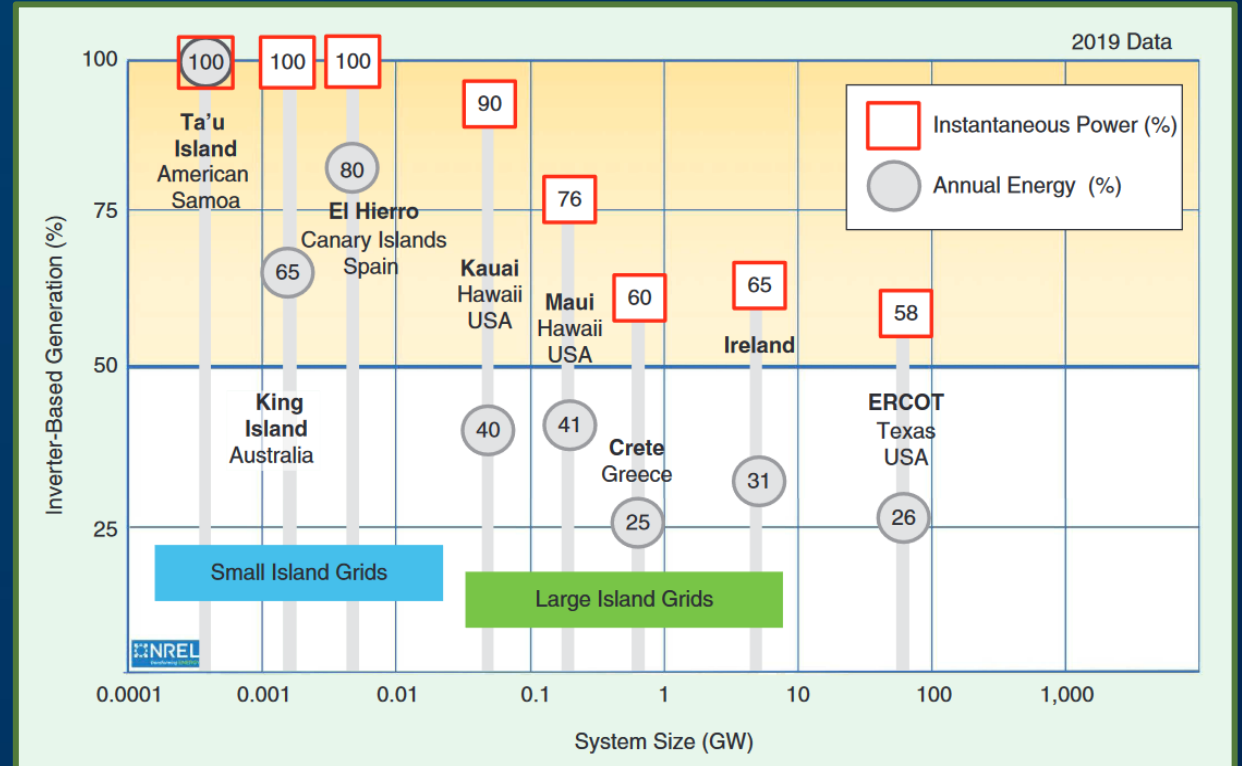
- Droop-e

Power Systems Simulation Lead at encoord



Changing Power Systems

- New stability classification: 'Converter-driven Stability'
- Numerous oscillatory events with unusual, higher frequency spectrums being observed



A. Hoke, V. Gevorgian, S. Shah, P. Koralewicz, R. W. Kenyon, and B. Kroposki, "Island Power Systems With High Levels of Inverter-Based Resources: Stability and Reliability Challenges," *IEEE Electrification Magazine*, vol. 9, no. 1, pp. 74–91, Mar. 2021.

Fundamental Device Differences – Simulation Perspective

Synchronous Generators; partitioned / narrow bandwidth

- Natural timescale separation; predictable
- Physics dominated dynamics
- Rotors yield deterministic local bus frequencies
- Dovetails with quasi-static phasor (QSP) simplifications

Inverter-based Resources; continuous / wide bandwidth

- Cascaded PI controllers; no 'natural' separation
- Current controller feedback; interacts with network transients
- Mathematically, tend to negate some of the QSP simplifications

A PSCAD Story

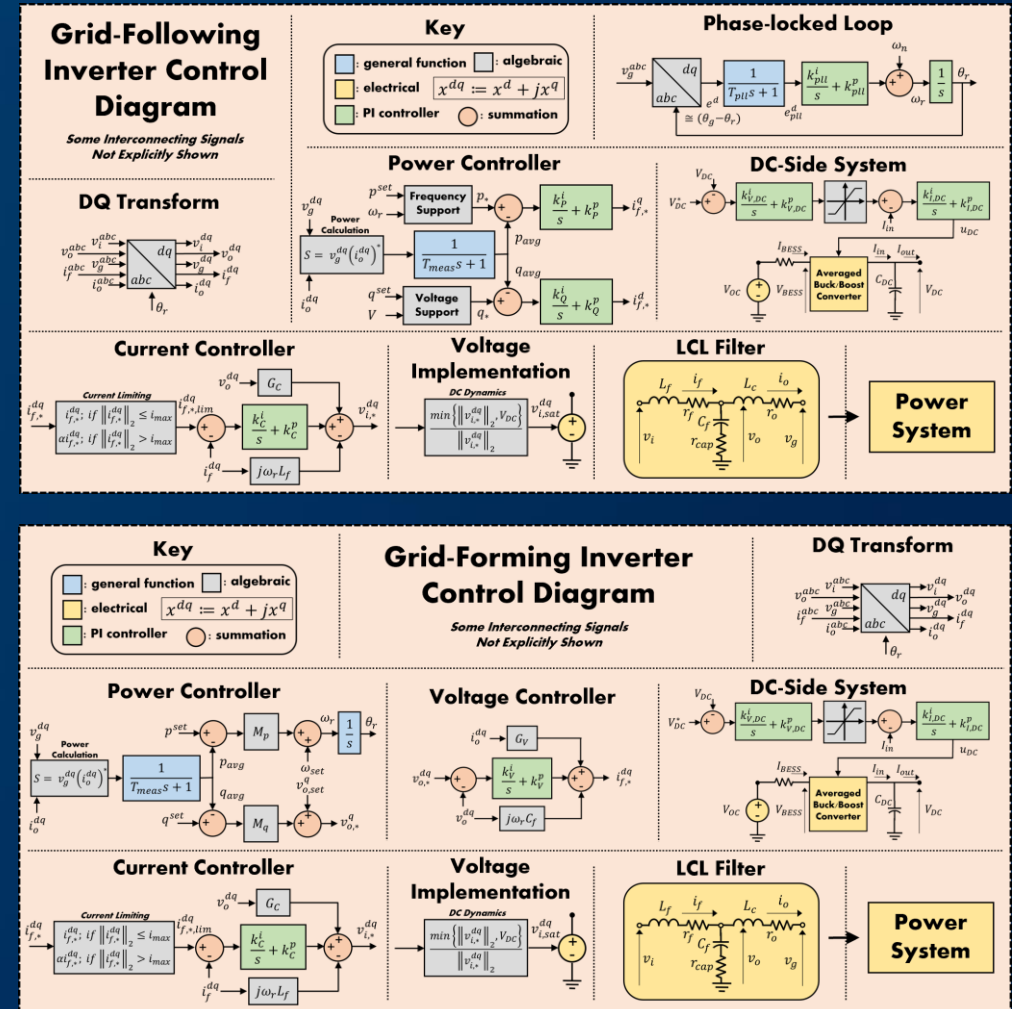
Generic Inverter Models

Open source / Scalable

Filter dynamics

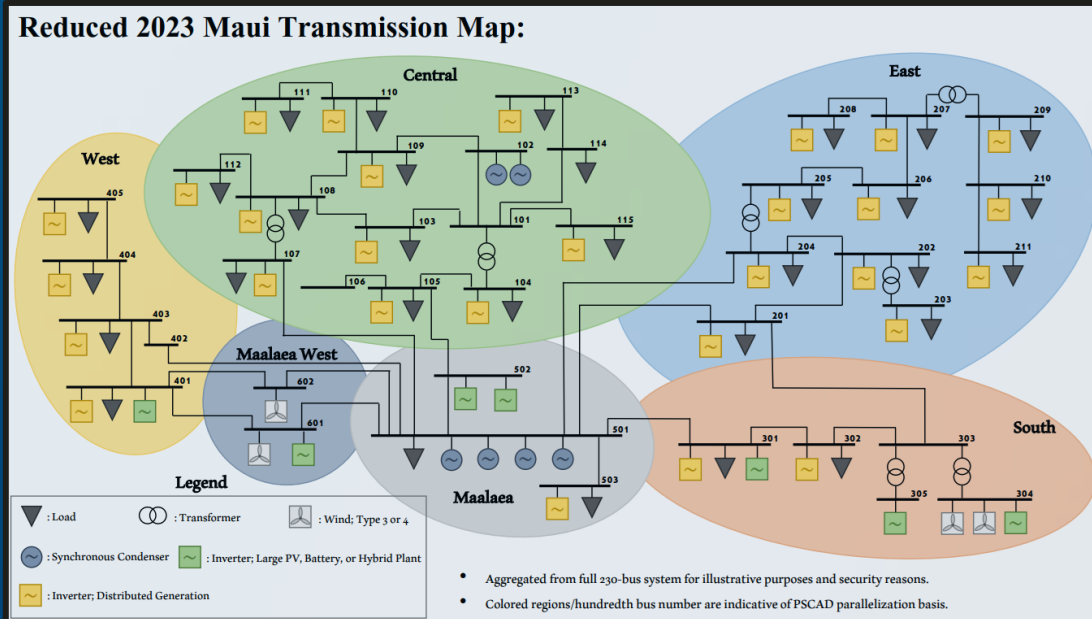
Current/power/voltage controllers

Limiting / DC - side dynamics



R. W. Kenyon, A. Sajadi, A. Hoke, and B.-M. Hodge, "Open-Source PSCAD Grid-Following and Grid-Forming Inverters and A Benchmark for Zero-Inertia Power System Simulations," in *2021 IEEE Kansas Power and Energy Conference (KPEC)*, Apr. 2021, pp. 1–6.

The Maui System – Validated to Field Data



Region	Generation: Transmission Connected Type	Rating (MVA)	Output (MW/Mvar)	Distributed Generation* (N/MW/Mvar)	Load (N/MW/Mvar)
Central	2x Synchronous Condensers 4x Hydro Generators	29.1 6.4	0.0 / 0.0 0.0 / 0.0	66 / 41.1 / -3.1	37 / 54.8 / 14.6
East	None	n/a	n/a	33 / 12.1 / -1.3	17 / 11.1 / 1.2
South	2x Type 4 Wind 1x Battery Energy Storage*** 1x Utility Solar 1x Hybrid Power Plant	24.0 10.0 2.9 19.1	21.0 / 0.0 0.0 / 0.0 2.7 / 0.0 0.0 / 0.5	27 / 30.5 / -2.2	9 / 38.4 / 3.2
West	1x Utility Solar	2.9	2.7 / 0.0	42 / 17.4 / -1.8	14 / 33.8 / 4.0
Maalaea	3x Synchronous Generators 4x Synchronous Condensers 2x Hybrid Power Plant	21.0 107.2 80.0	5.7 / 6.9 0.0 / 14.9 5.7 / 5.3	3 / 3.2 / -0.3	13 / 6.6 / 3.4
Maalaea West	2x Type 3 Wind 1x Battery Energy Storage***	56.7 10.0	3.9 / 0.0 0.0 / 0.0	0 / 0.0 / 0.0	0 / 0.0 / 0.0
Totals	<i>Synchronous: 13</i> <i>Inverter Based: 11</i>	163.7 205.5	5.7 / 21.8 35.9 / 5.8	171 / 104.3 / -8.7	90 / 144.7 / 26.4

PSCAD model built with generic inverter models.

Parallelized; 30 cores on a dedicated machine; hours for a 15 second simulation.

This is a SMALL system!

R. W. Kenyon, B. Wang, A. Hoke, J. Tan, C. Antonio, and B.-M. Hodge, "Validation of Maui PSCAD Model: Motivation, Methodology, and Lessons Learned," in *2020 52nd North American Power Symposium (NAPS)*, Apr. 2021, pp. 1–6.

PSCAD vs. PSSE

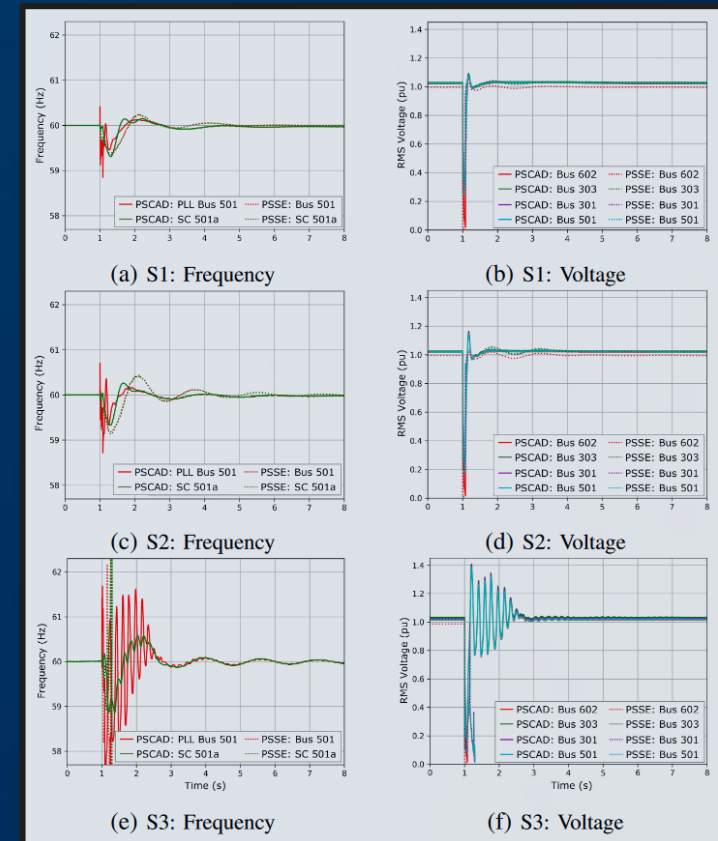
	S1		S2		S3		S4		S5		S6		S7	
E1	Y	Y	Y	Y	N	Y	N	N	N	N	Y	Y	X	N
E2	Y	Y	Y	Y	N	Y	N	N	N	N	Y	Y	X	N
E3	Y	Y	Y	Y	N	Y	N	N	N	N	Y	Y	X	N
E4	Y	Y	Y	Y	N	Y	N	N	N	N	Y	Y	X	N
E5	Y	Y	Y	Y	N	Y	N	N	N	N	Y	Y	X	N
E6	Y	Y	Y	Y	N	Y	N	N	N	N	Y	Y	X	N
E7	Y	Y	Y	Y	N	Y	N	N	N	N	Y	Y	X	N
E8	Y	Y	Y	Y	N	Y	Y	N	N	N	Y	Y	X	N
E9	Y	Y	Y	Y	Y	Y	Y	N	Y	N	Y	Y	X	N
E10	Y	Y	Y	Y	Y	Y	Y	N	N	N	Y	Y	X	N
E11	Y	Y	Y	Y	Y	Y	N	N	n/a	n/a	Y	Y	n/a	n/a

	Key
Y	PSSE sim successful
N	PSSE sim cannot be completed
X	PSSE sim cannot be run
Y	PSCAD sim successful
N	PSCAD steady state is unstable

**successful implies computational success only; in some cases, substantial UFLS/protective action would have occurred*

S1-> S5: march towards fewer voltage forming devices

Oscillations present after synchronous machines were removed - S3 (66% MVA reduction)



R. W. Kenyon, B. Wang, A. Hoke, J. Tan, and B.-M. Hodge, "Comparison of Electromagnetic Transient and Phasor Dynamic Simulations: Implications for Inverter Dominated Systems," in *2023 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, IEEE, 2023, pp. 1–5.

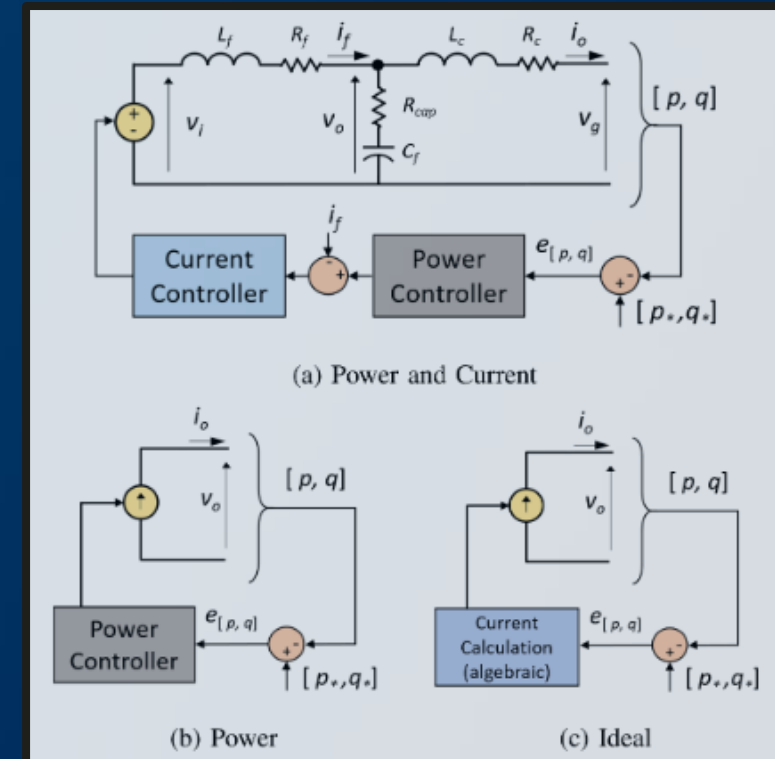
PSCAD vs. Itself

Power and Current contains current controller/output filter

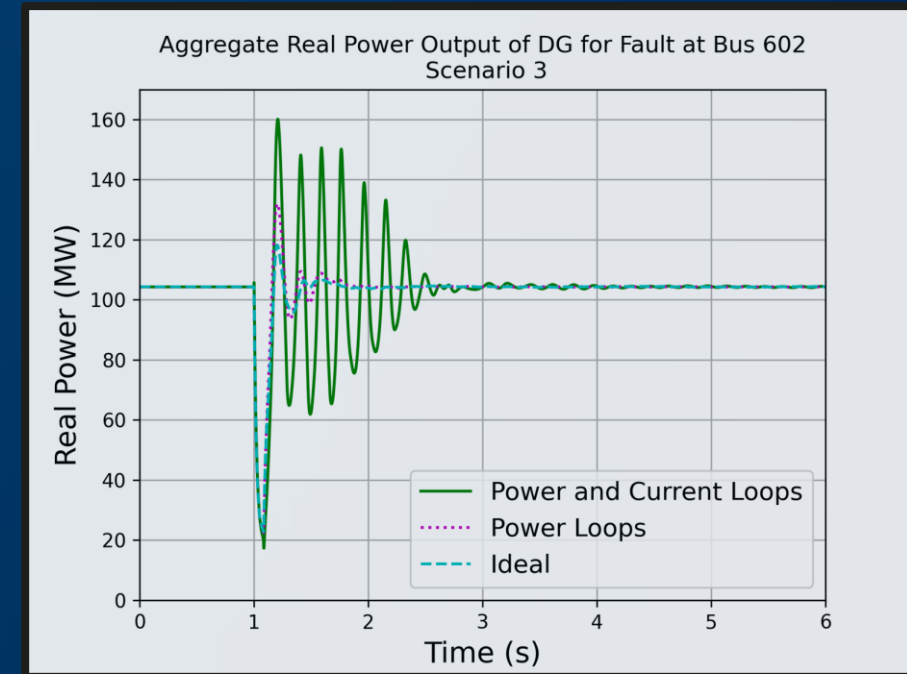
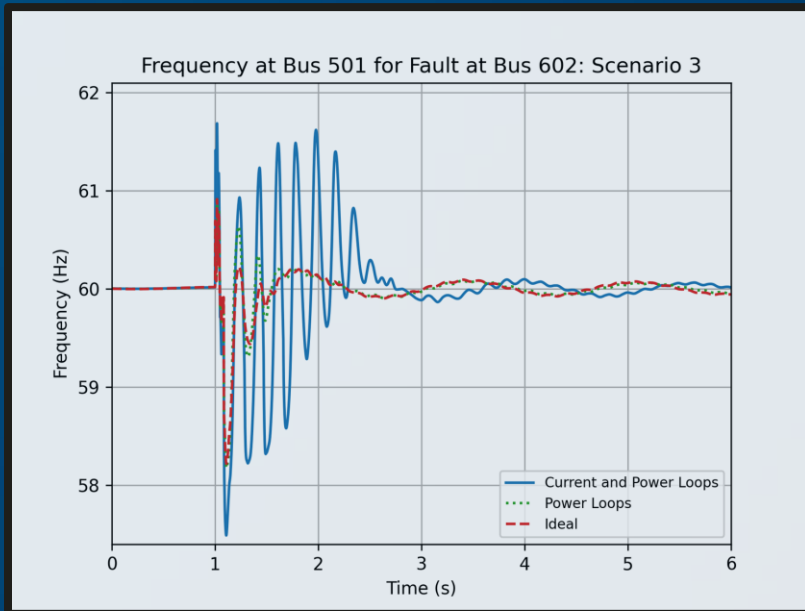
Power, a rough QSP type device level proxy?

All types with a phase-locked loop

Systematic reduction of only the **DG** inverter models
171 devices; ~100 MVA aggregate rating



PSCAD vs. Itself



An anecdote; a single GFM device (another paper) solved this oscillatory issue in the full model.

R. W. Kenyon, A. Sajadi, A. Hoke, and B.-M. Hodge, "Criticality of Inverter Controller Order in Power System Dynamic Studies – Case Study: Maui Island," *Electric Power Systems Research*, vol. 214, p. 108789, Jan. 2023, doi: [10.1016/j.epsr.2022.108789](https://doi.org/10.1016/j.epsr.2022.108789).

So Where Does This Leave Us?

- **System-wide, EMT type simulations are an enormous effort to develop, and extremely computationally intensive to run.**
- **Some of the bedrock simplifications of QSP type simulations also simplify pertinent, controller driven dynamics.**
- **QSP approaches are still vastly applicable, but there are operational periods that undeniably demand more detail.**

Co-simulation? Exchanging Between Tools

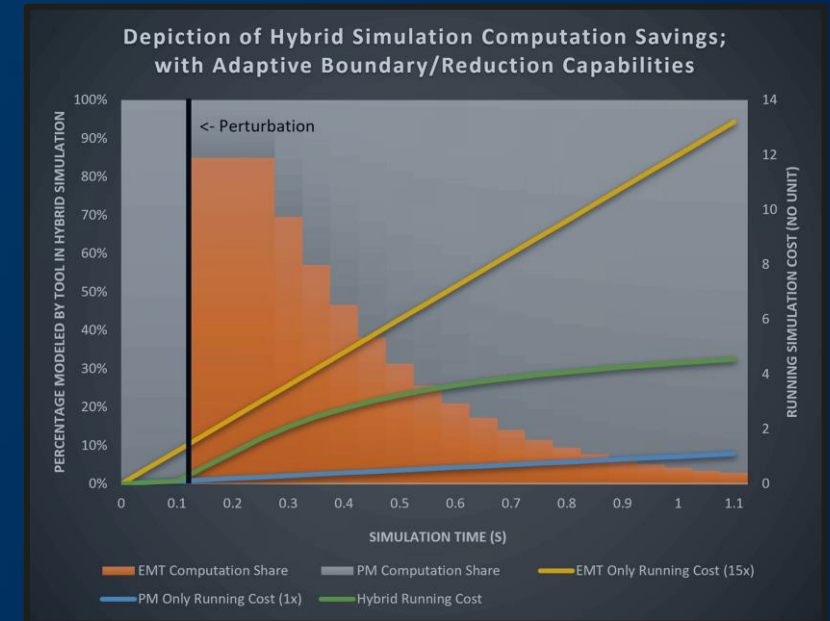
EMT when detail is needed; QSP when it is not.

These are challenging...

- separate simulation / software tools
- boundaries, boundaries, boundaries
- interfaces / network equivalents

Our Research: Hybrid Simulations

As a formulation solution



America's
SEED FUND
SBIR.STTR

Intra-simulation Detail Modifications

If full order models are introduced (all detail is available), can intra-simulation singular perturbation / manifold type reductions be made?

Singular perturbation on the fly: an adaptive application

$$\begin{aligned}\dot{x}_s &= F_s(x, \eta, \epsilon) \\ \epsilon \dot{x}_f &= F_f(x, \eta, \epsilon) \\ \epsilon &\rightarrow f(t) ?\end{aligned}$$

Autonomous Boundary Identification

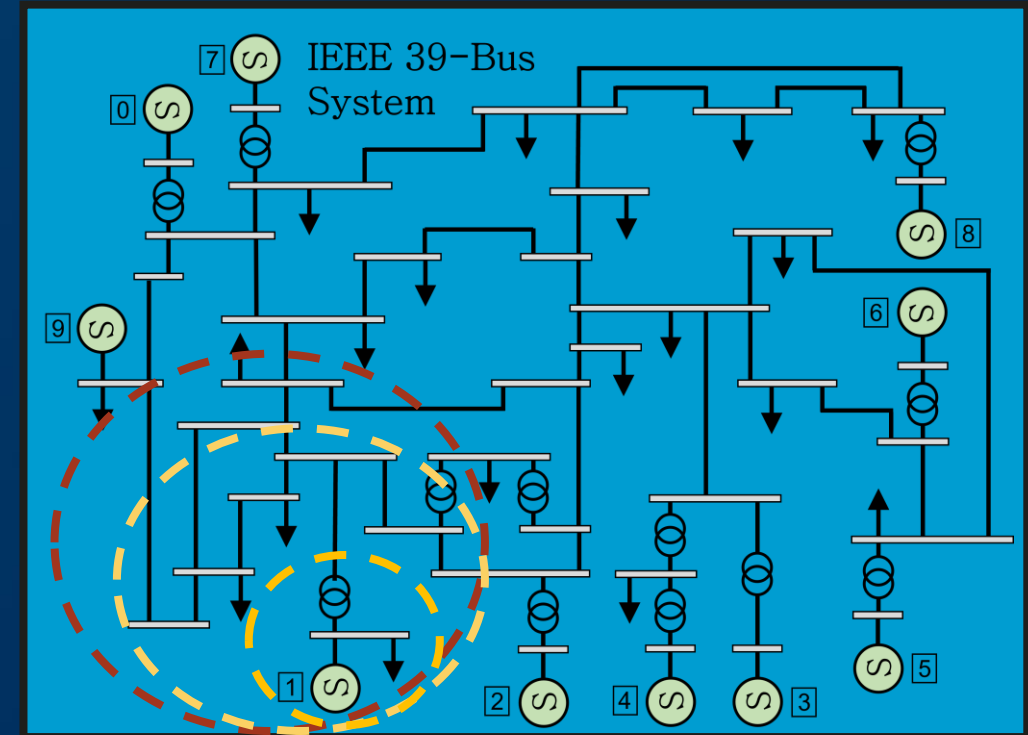
Topological / temporal tracking

Metrics:

- voltage forming capacity and/or inertia
- short circuit ratio
- zero sequence magnitudes

Analytic:

- high frequency components
- impedance spectroscopy
- larger state rate of changes



Computational Structure

Will interface handling be inherent within the computational structure?

Variable, partitioned approach:

$$\mathbf{m}^t + \mathbf{n}^t = \mathbf{P}, \quad \forall t$$

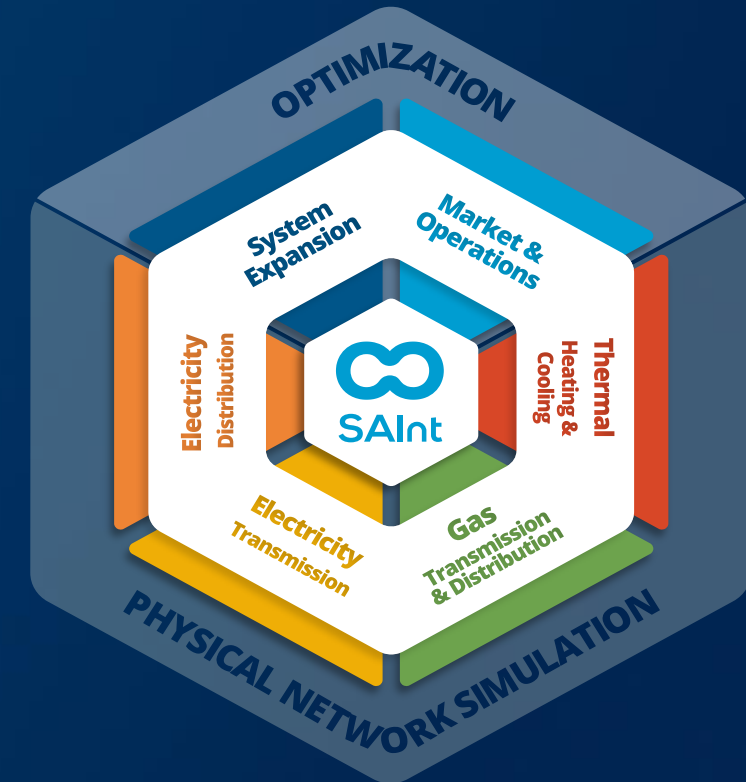
$$\dot{\mathbf{x}}_m = \mathbf{f}_m(\mathbf{x}_m, \mathbf{y}_n, \boldsymbol{\eta}, t)$$

$$\mathbf{0}_n = \mathbf{g}_n(\mathbf{x}_m, \mathbf{y}_n, \boldsymbol{\gamma}, t)$$

Simultaneous, with coefficient updating

Goal is a Native, Hybrid Simulation Tool

- Building dynamic simulation capabilities;
a great time to ask foundational questions!
- Integrated into our existing, commercially available, SAInt software.



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