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Plan the Energy Future

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

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ESIG

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Fall Technical Workshop

Brief Wallace History

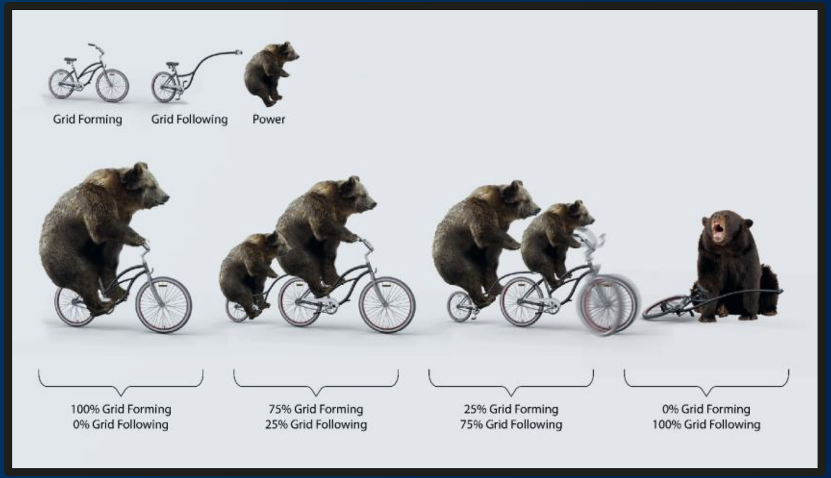
NREL 2017 - 2022:

- 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

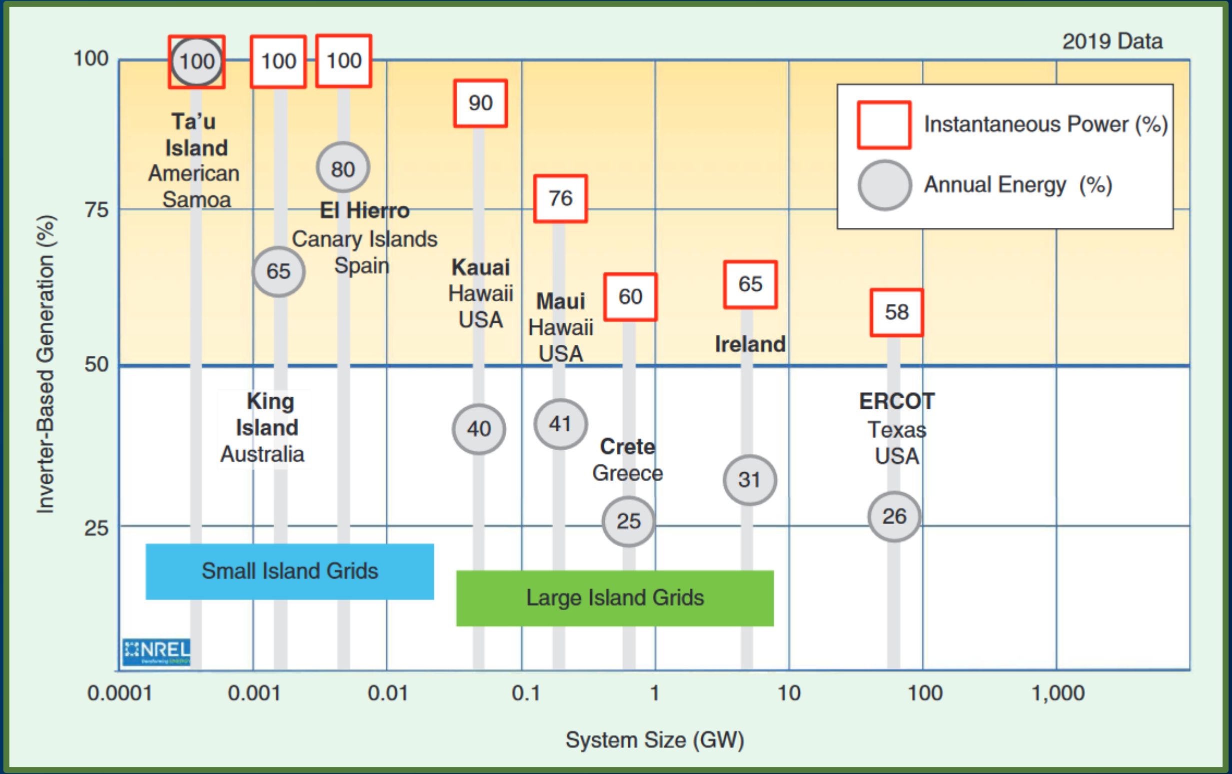


NATIONAL RENEWABLE ENERGY LABORATORY

University of Colorado Boulder

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.

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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

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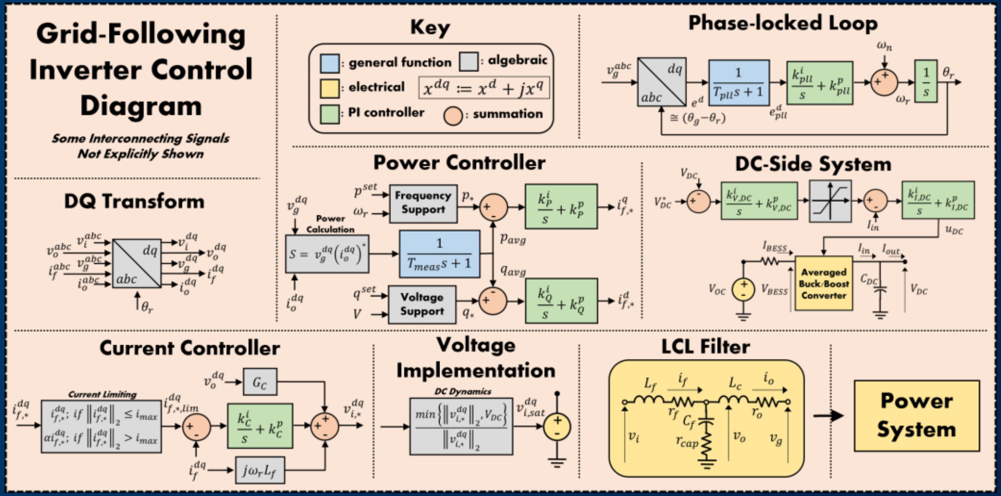
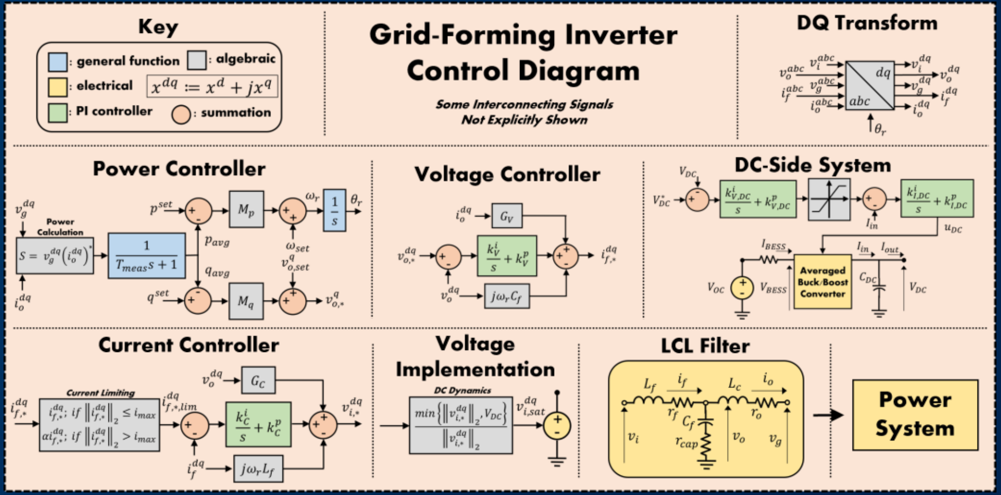
Generic Inverter Models

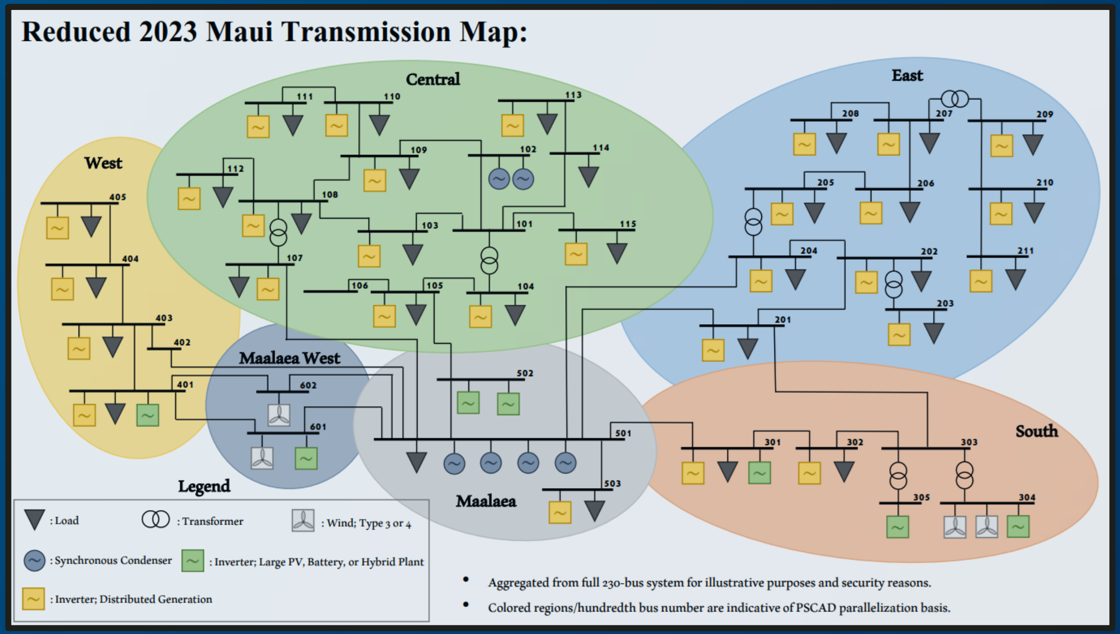
- Open source / Scalable
- Filter dynamics
- Current/power/voltage controllers
- Limiting / DC - side dynamics





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

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.

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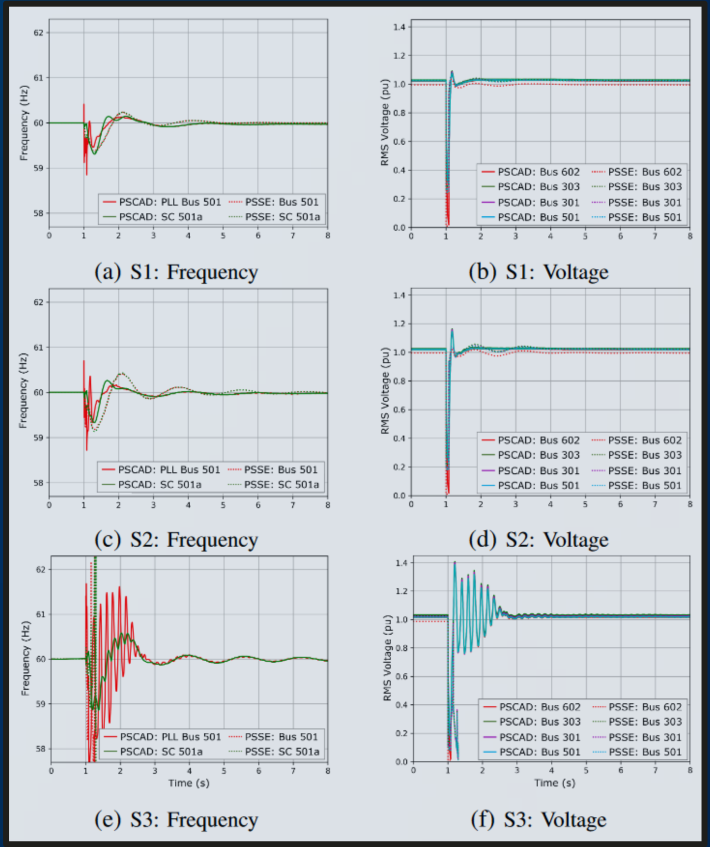
PSCAD vs. PSSE

	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.

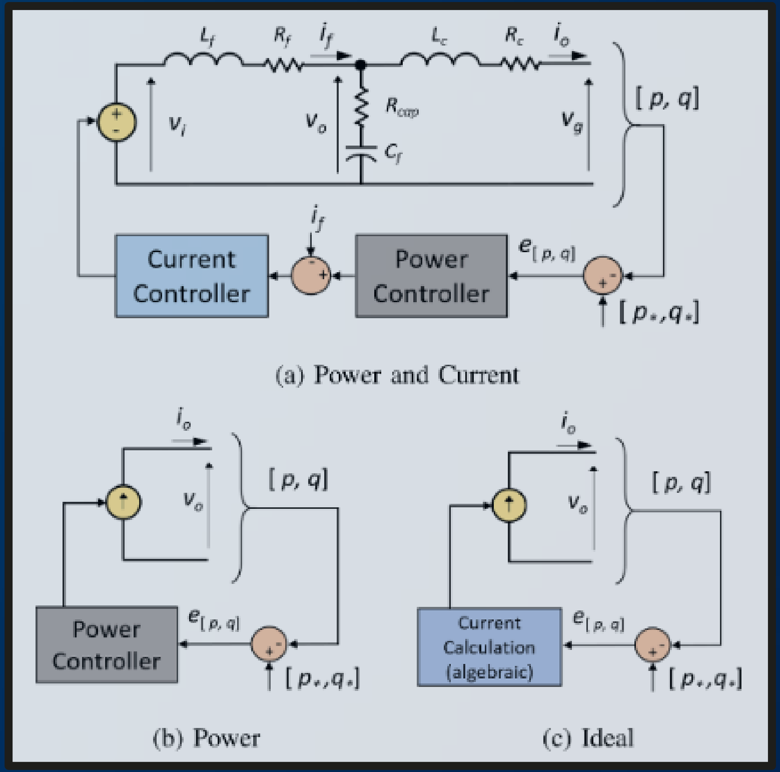
PSCAD vs. Itself

Power and Current contains current controller/output filter

Power, a rough QSP type device level proxy?

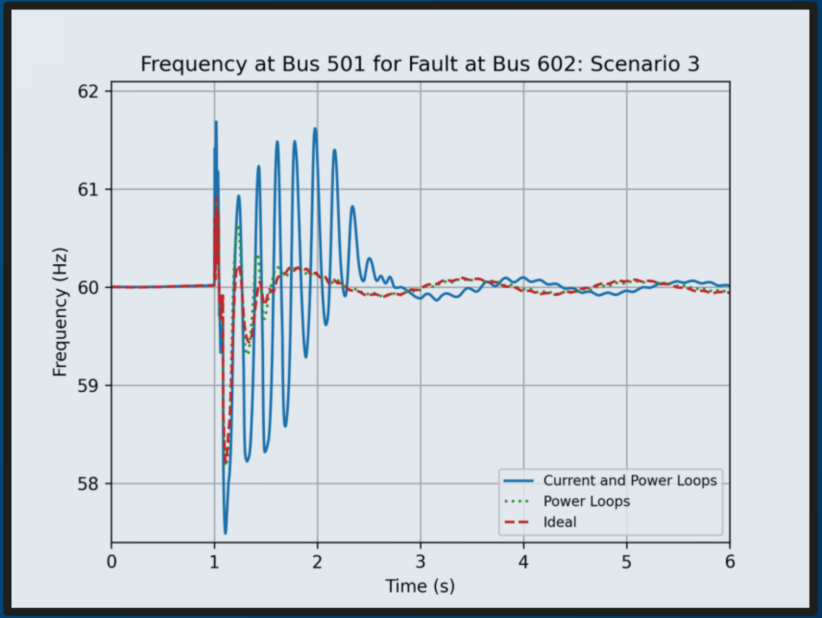
All types with a phase-locked loop

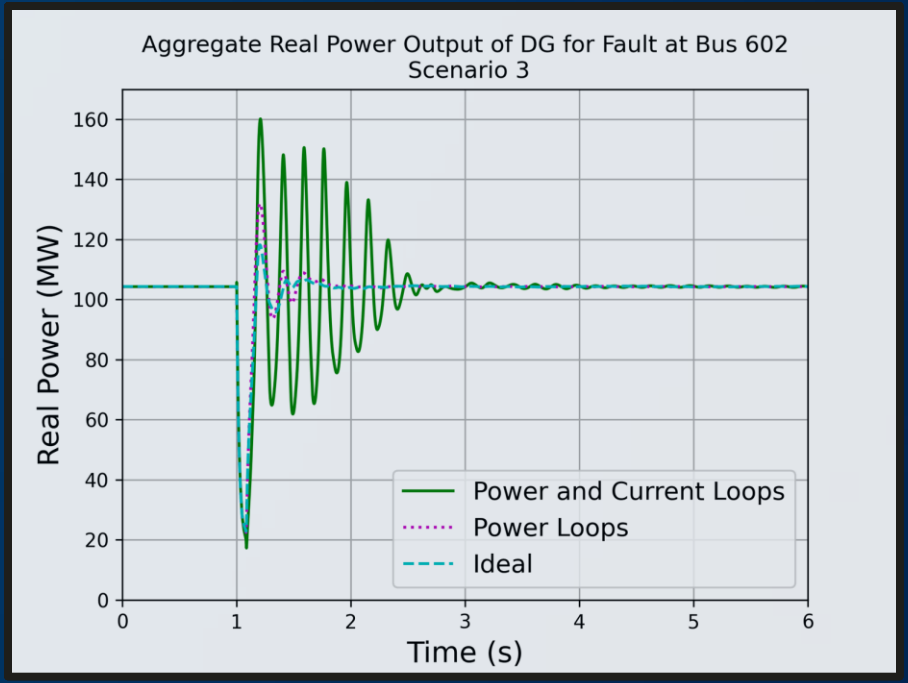
Systematic reduction of only the **DG** inverter models
171 devices; ~100 MVA aggregate rating



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.

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.

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

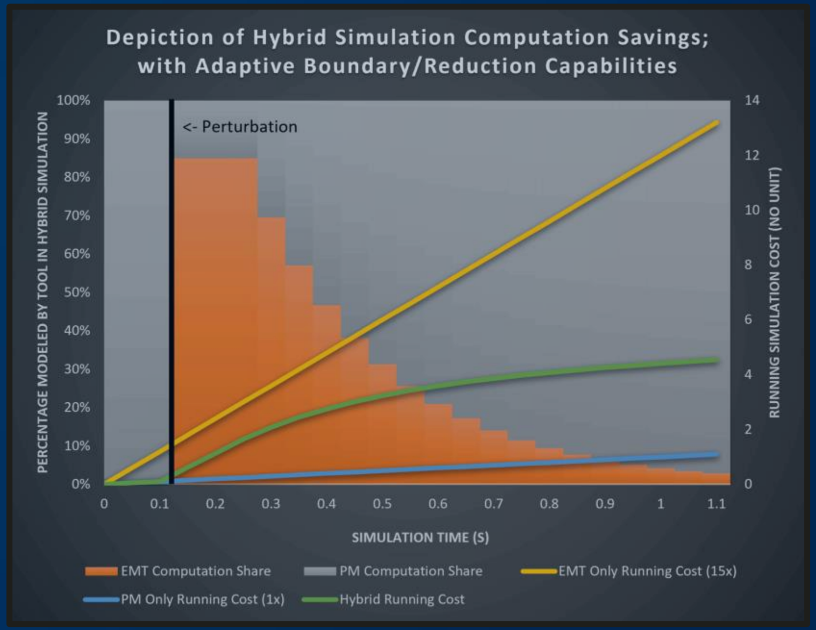
EMT when detail is needed; QSP when it is not.

These are challenging…

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

Our Research:
Hybrid Simulations

As a formulation solution



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

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

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Autonomous Boundary Identification

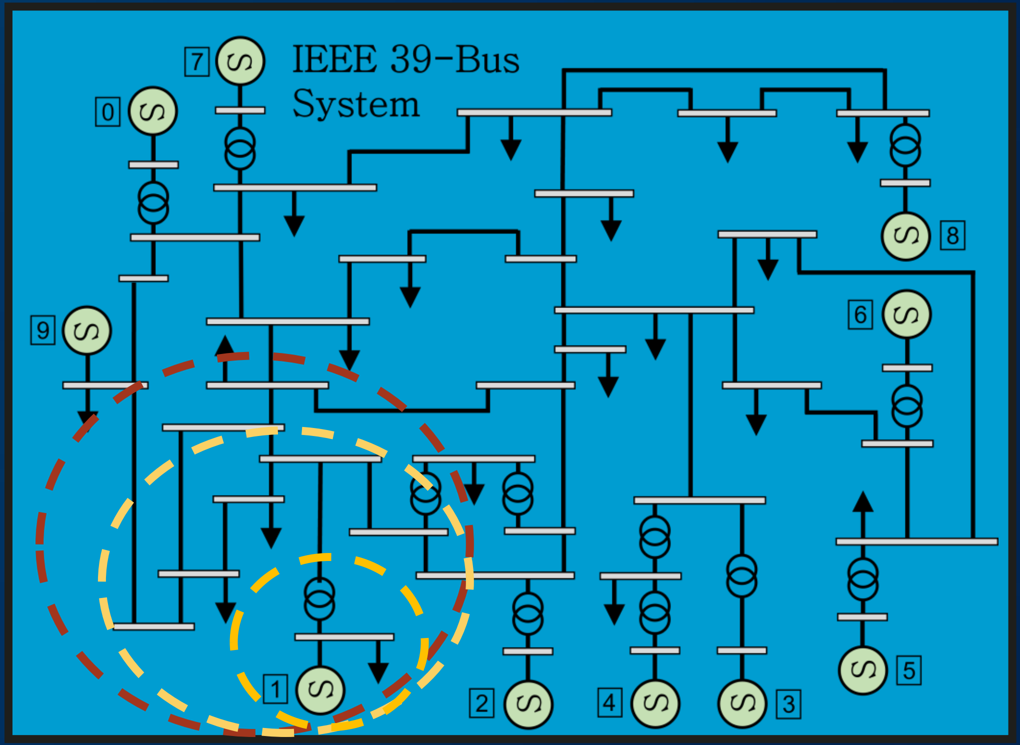
Topological / temporal tracking

Metrics:

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

Analytic:

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



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Computational Structure

Will interface handling be inherent within the computational structure?

Variable, partitioned approach:

$$\boldsymbol{m}^t + \boldsymbol{n}^t = \boldsymbol{P}, \qquad \forall \boldsymbol{t}$$
$$\dot{\boldsymbol{x}}_m = \boldsymbol{f}_m(\boldsymbol{x}_m, \boldsymbol{y}_n, \boldsymbol{\eta}, \boldsymbol{t})$$
$$\boldsymbol{0}_n = \boldsymbol{g}_n(\boldsymbol{x}_m, \boldsymbol{y}_n, \boldsymbol{\gamma}, \boldsymbol{t})$$

Simultaneous, with coefficient updating

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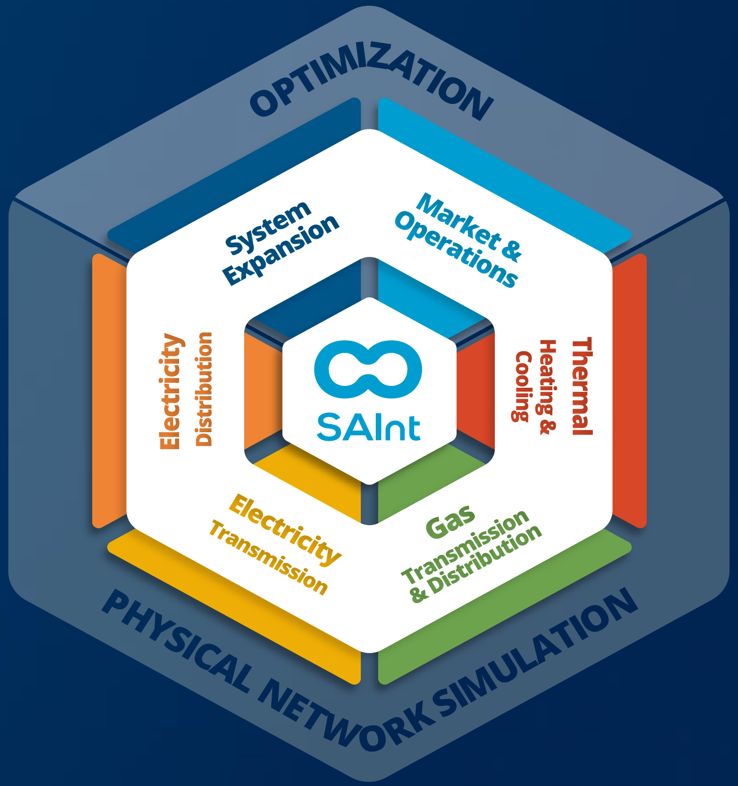
Goal is a Native, Hybrid Simulation Tool

- Building dynamic simulation capabilities;

  a great time to ask foundational questions!

- Integrated into our existing, commercially available, SAInt software.



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