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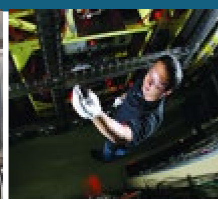
Improving the Accuracy of Modeling/Simulation Solvers to Better Understand the Impact of Inverter-Based Resources and other Fast Dynamics on Power Grids



PRESENTED BY

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Sandia National Labs

NASPI Work Group Virtual Meeting

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U.S. DEPARTMENT OF ENERGY NNSA

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Background and Motivation

Among the ways in which Inverter-Based Resources (IBRs) differ from traditional synchronous generation:

1. Grid interconnection is realized via electronic converters.
2. Injected power from IBRs is often highly variable and intermittent.

1. ➔ Problem of simulating the interface of a fast dynamic component (electronic converter) with a slower system (power grid).

2. ➔ Need to run simulations spanning longer time frames than those associated with typical transient stability simulations.

Combined, 1. and 2. ➔ Simultaneous simulation of fast and slow dynamics.

High penetration of IBRs ➔ Low inertia grid ➔ Increased rate of change of frequency (ROCOF) in response to transient events.

Numerical integration algorithms currently deployed in power system dynamic simulation tools were not designed to study these vastly different dynamic phenomena in a single simulation scenario.

What is needed are:
Better numerical solvers to simulate fast & slow dynamics on longer time frames.

Current Practice

Dynamics	Timescale	Simulation Toolsets	Examples
Electromagnetic Transients (EMTP)	10^{-6} – 10^{-2} seconds	Three phase simulation, e.g., EMTP, Spice	• Faults • Voltage spikes • Harmonics
Transient Stability	10^{-2} – 100 seconds	Positive sequence simulation, e.g., PSLF, PSSE, PowerWorld	• Inertia dynamics • Generator controls • Induction motor stalls
Extended Term Dynamics	100 seconds – hours	Capability gap – methods such as analysis of set of power flow cases are used	• Automatic Generation Control • FIDVR • Frequency response
Steady State	hours – years	Positive sequence power flow, e.g., solving nonlinear algebraic equations	• Equipment overloading • Reactive resource mgmt • System losses and economics

Current Practice

Power system dynamics consist of a set of differential-algebraic equations (DAE) of the following form:

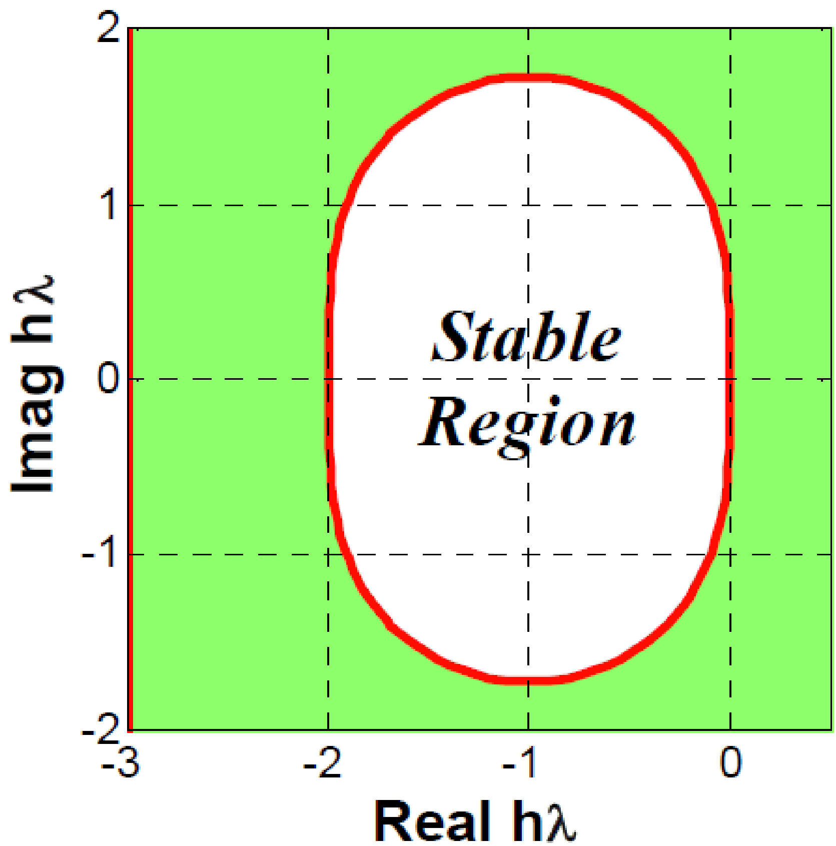
$$\dot{x} = f(x, v) \quad (1)$$

$$0 = g(x, v) = i(x, v) - Yv \quad (2)$$

x = vector of state variables
v = vector of bus voltages (real and imaginary parts)
i = vector of current injections (real and imaginary parts)
Y = network admittance matrix

Current Practice: Runge-Kutta Method

The second-order Runge-Kutta (RK2) method is one of the most widely used numerical integration schemes in existing commercial dynamic simulation software tools.



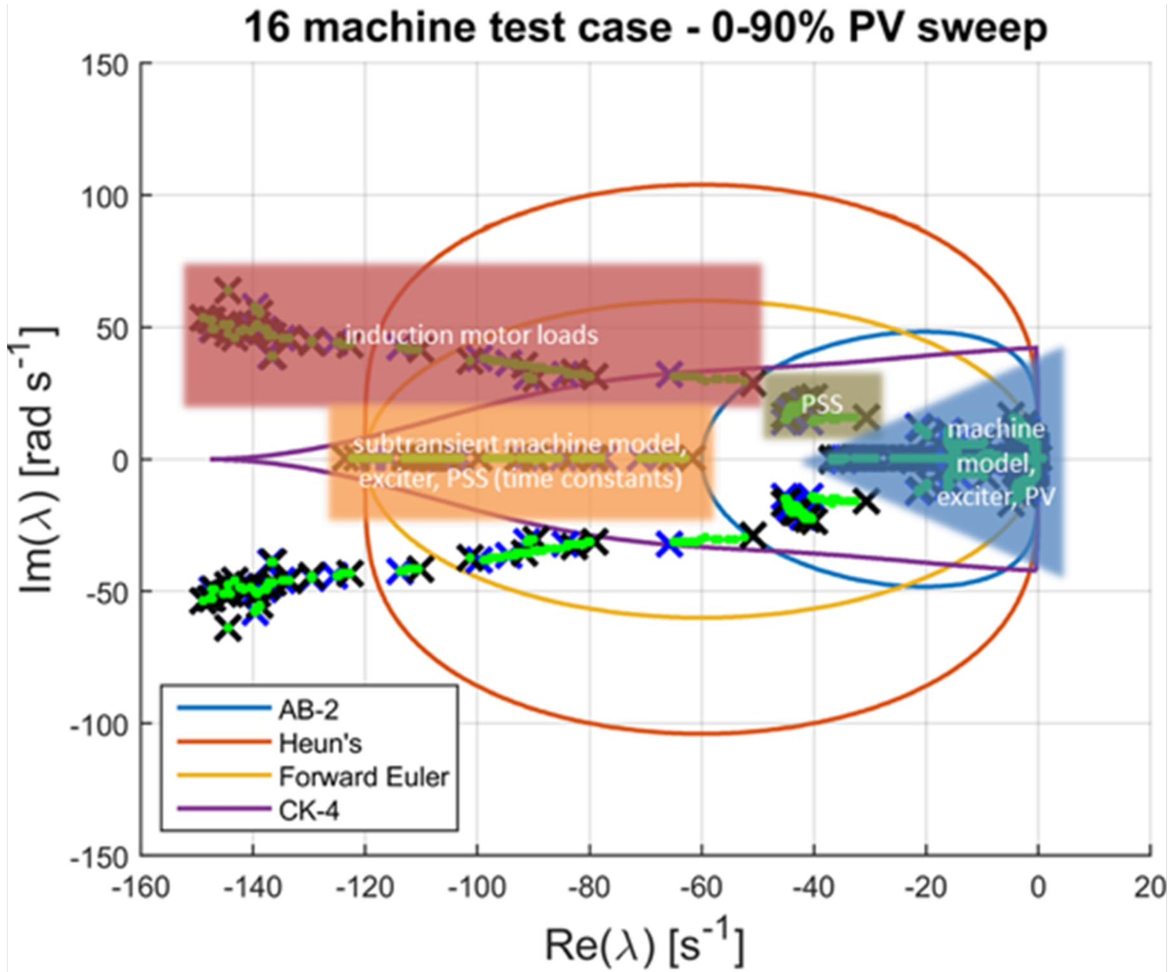
Stability region of RK2 method
h = integration time step
$\dot{x} = \lambda x$ is system being solved

To maintain stability, h and/or $|\text{Real }(\lambda)|$ must remain small → computation times will be relatively long and/or fast transients will not be accurately captured.

Plot from: S. Kim and T. J. Overbye, "Optimal Subinterval Selection Approach for Power System Transient Stability Simulation," *Energies*, vol. 8, pp. 11871-11882, 2015.

Variable Time Step Algorithm

- In the **variable time step** method, the time step can increase as fast transients subside; conversely, the time step can be reduced to capture fast transients.
- This permits a reduction in the number of necessary iterations, supporting the use of more complex integration schemes.
- This is accomplished through time step control, which estimates error at each iteration and adjusts the time step to meet a tolerance threshold.

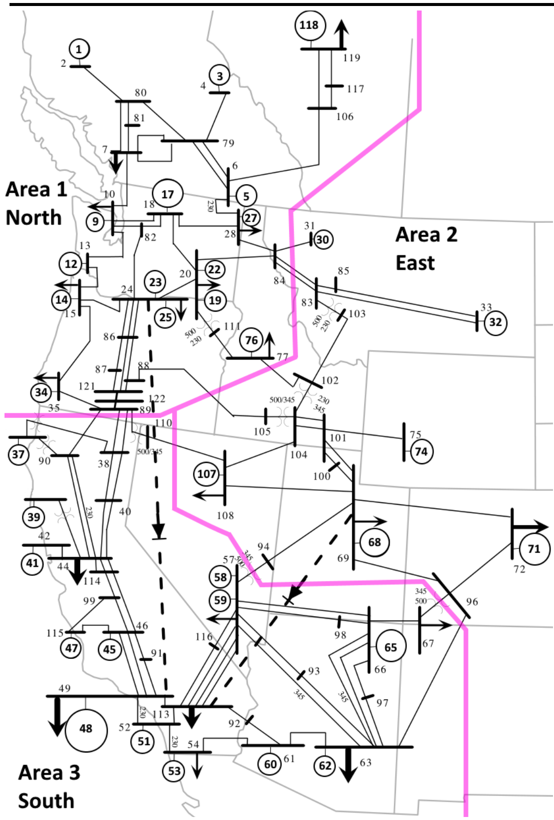


Regions of stability for four candidate integrators for a given step size. The poles of a representative power system are shown for reference.

Plot from: R. Concepcion, M. Donnelly, R. Elliott, and J. Sanchez-Gasca, "Extended-Term Dynamic Simulations with High Penetrations of Photovoltaic Generation," Sandia Technical Report, SAND2016-0065, 2016.

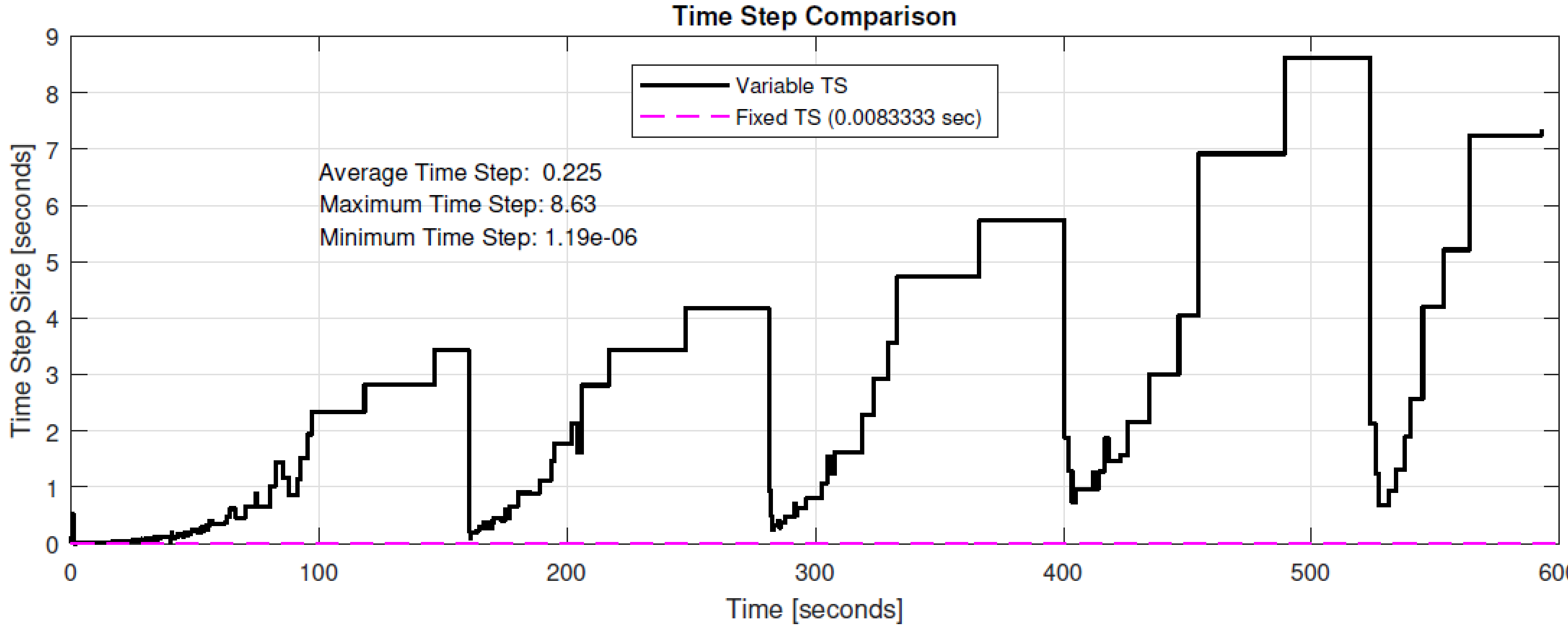
Variable Time Step Example

	Step Size [seconds]				Solutions Per Step				
Method	Max	Min	Ave	Total Steps	Ave	Max	Total Slns.	Sim. Time [seconds]	File Size [bytes]
Huen's	0.0083	8.33E-03	0.0083	72,001	2	2	144,002	483.64	778,259,381
ode23/ ode23t	8.6300	1.19E-06	0.0570	2,662	2	775	6,632	53.4	32,772,591
ΔRatio	0.001	7,000	0.146	27.05	1	0.003	21.71	9.06	23.75

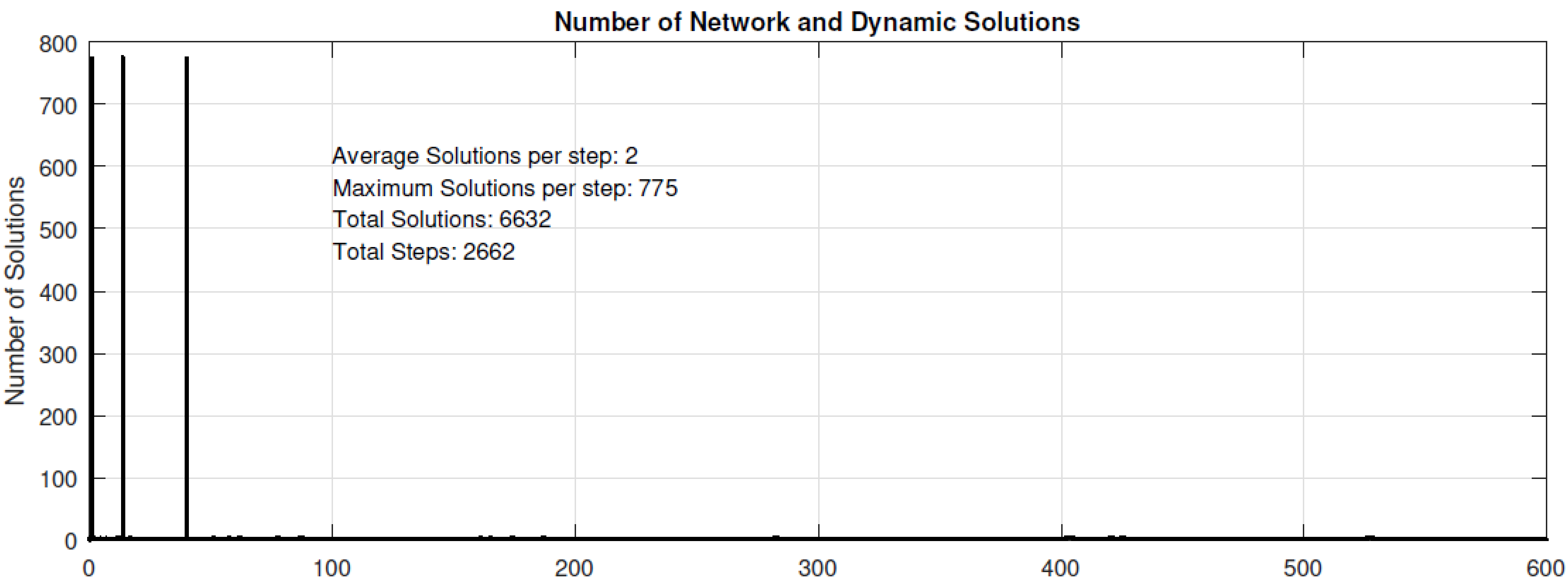


- VTS method is labeled ode23/ode23t. Simulation runs in PST (Matlab-based Power System Toolbox).
- System modeled is MiniWECC: 122 buses, 171 lines, 88 loads, 34 generators, 623 states.
- Event is a +435 MW load step on Bus 2 at t=1 sec.
- Each area has identical AGC that acts at t=40 sec and every 2 minutes thereafter.
- Simulation is run for 10 mins (600 secs).
- Results show VTS runs 9 times faster than FTS with a 24 times smaller output file size.

Variable Time Step Example



Comparison of time step size for variable time step and fixed time step methods.

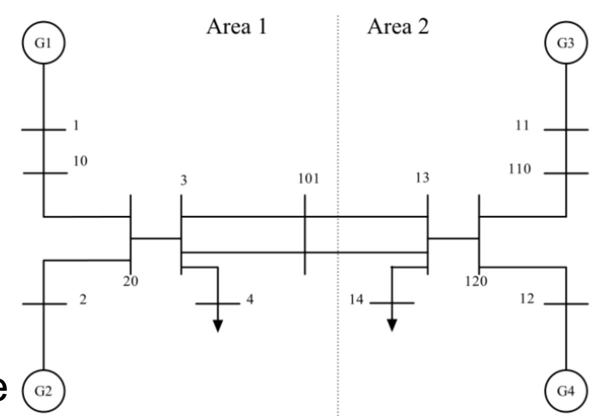


Plot of number of network (algebraic) and dynamic (ODE) solutions for VTS method.

Sensitivity Analysis of VTS Method

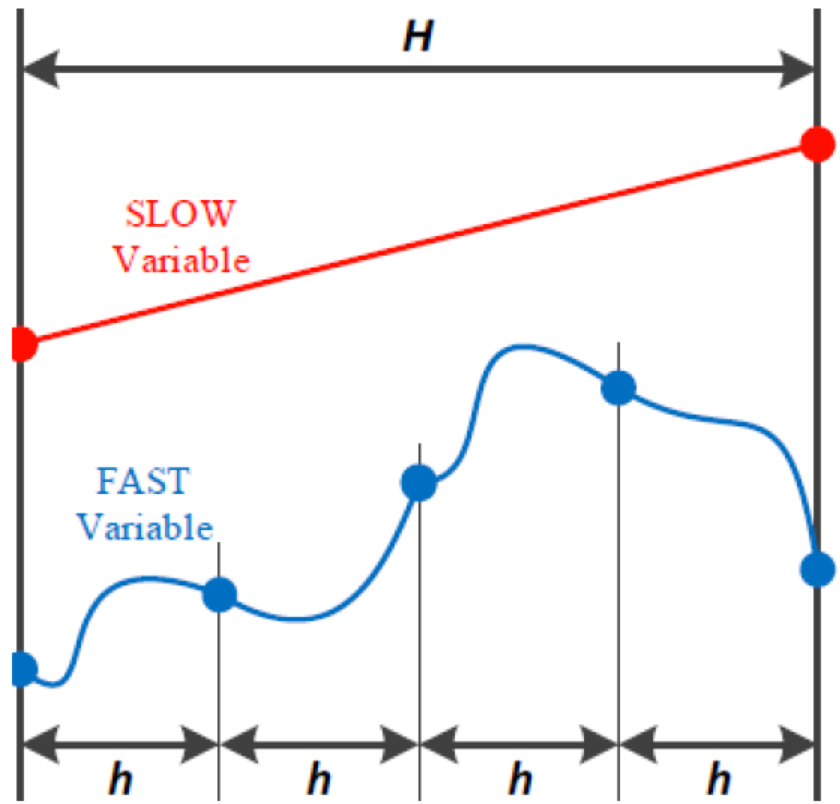
	FTS	VTS									
		Base Case	Initial Step Size			Rel./Abs. Tolerance			ODE Solvers		
			10^{-5}	10^{-2}	10^{-1}	10^{-3}	10^{-4}	10^{-5}	ode15s	ode113	ode23
Avg Error [%]	0.0	3.4e-3	7.4e-4	4.5e-4	3.0e-3	1.0e-2	7.3e-3	3.5e-3	3.1e-4	5.5e-5	2.7e-5
Total Comp Time [s]	333.5	176.5	187.0	173.4	169.4	16.5	30.2	92.6	117.4	263.9	280.3
Avg Time Step [s]	0.004	0.010	0.010	0.001	0.010	0.229	0.078	0.025	0.014	0.008	0.007
Max Time Step [s]	0.004	21.900	19.900	14.100	23.400	21.900	21.900	21.900	10.000	0.156	0.128
Min Time Step [s]	4e-3	1.6e-5	1.0e-5	1.6e-5	1.6e-5	3.9e-4	1.2e-4	4.2e-5	3.9e-5	5.8e-5	8.8e-6
Avg Sol per Step	N/A	2	2	2	2	4	3	2	2	3	2
Max Sol per Step	N/A	100	96	96	96	104	100	100	96	27	8
Total Sols	N/A	48075	48738	50566	47570	3722	7906	20984	30956	87794	77082
Total Steps	N/A	23644	23849	24251	23629	1049	3087	9553	17734	29150	35632

- Model simulated is Kundur two-area four-machine system.
- Event is a perturbation of governors to mimic solar variation due to cloud cover.
- Sensitivity is studied w.r.t. initial step size, error tolerance, and type of ODE solver.
- Minimal sensitivity to initial step size.
- Different error tolerances have large impact on computation time with minimal impact on solution accuracy.
- ODE solver type greatly impacts computation time and accuracy (non-stiff solvers are slower but more accurate than stiff solvers).



Multi-Rate Algorithms

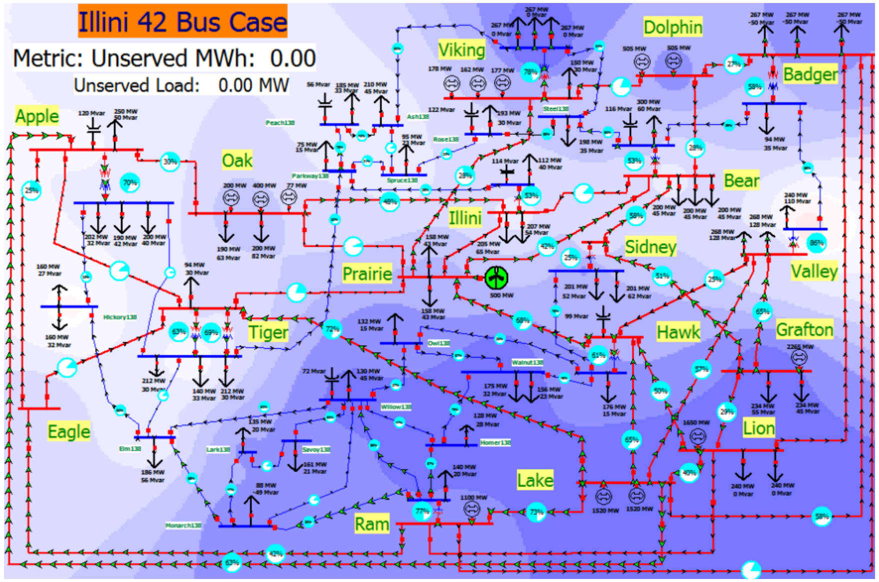
- Another approach to extended simulation times is the use of **multi-rate methods**.
- In this approach, h is a small timestep for fast changing variables.
- H is a longer time step for slow changing variables.
- H is an integer multiple of h.
- In the figure, H = 4·h.



Plot from: S. Kim and T. J. Overbye, "Optimal Subinterval Selection Approach for Power System Transient Stability Simulation," *Energies*, vol. 8, pp. 11871-11882, 2015.

Multi-Rate Method Examples

42-bus synthetic grid for central Illinois



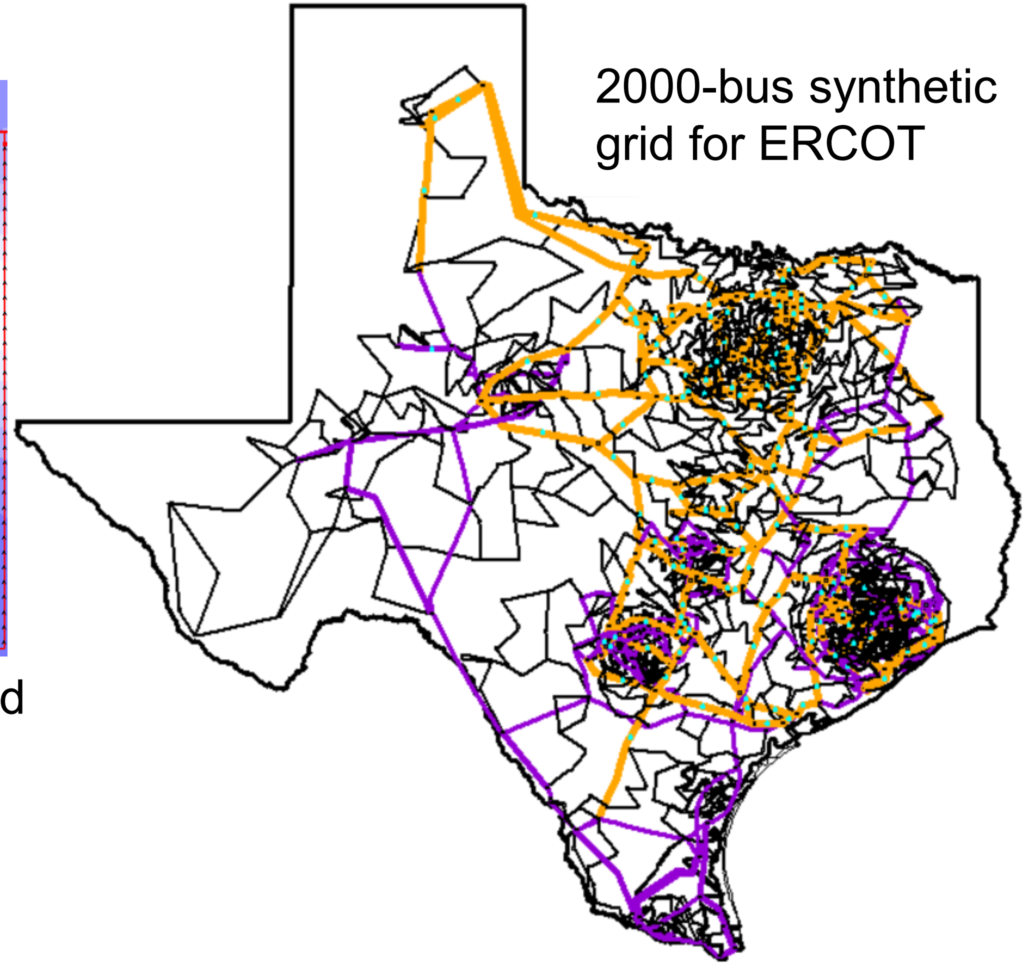
Computation times by integration method

System	Single Rate Reduced Time Step	Multirate Larger Time Step
42-Bus	2.02 s	0.24 s
2000-Bus	147.95 s	17.52 s

Mean squared error estimates by integration method

System	Single Rate Larger Time Step	Multirate Larger Time Step
42-Bus	Does Not Converge	7.60E-7
2000-Bus Rotor Angle	39.27	2.98E-7
2000-Bus Voltage Mag.	0.003	0
2000-Bus Voltage Angle	130.86	2.14E-7

2000-bus synthetic grid for ERCOT



MR method yields:

- More accurate results
- Approx. 9 times faster run times
- Better convergence than FTS

Other Approaches Being Investigated

- Parallelization techniques based on distributed computing to speed numerical solution of system equations.
- Improved error analysis of numerical methods to study systems with noise and modeling uncertainties ➔ uncertainty propagation.
- Improved modeling – AGC, grid forming and grid following inverters.
- Adaptive modeling framework – software that switches between classical transient simulation and long-term time sequenced power flow simulation.

Conclusions

- Rapidly increasing grid integration of IBRs is highlighting the need for numerical solvers better suited to simulate the fast and slow dynamics associated with inverter-connected PV systems over extended time frames.
- Existing commercial simulation toolsets were not designed to study these vastly different dynamic phenomena in a single simulation scenario.
- New numerical methods, improved models, and advanced software techniques are being developed to address the need for longer simulation times of systems with dynamics on widely varying time scales.