Paper No: 20PESGM3371

SAND2020-8062C

Improving Simulation Tools to Better Understand Impact of High PV Penetration in Power Grids

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Agenda

- Background and Motivation
- Current Practice
- Improving Existing Simulation Capabilities
- Conclusions
- Acknowledgements

Background and Motivation

- Two ways PV power plants differ from traditional synchronous generation:
  1. Grid interconnection is realized via electronic converters.
  2. PV power is inherently variable and intermittent.
- Item 1 → Problem of simulating the interface of a fast dynamic component (electronic converter) with a slower system (power grid).
- Item 2 → Need to run simulations spanning longer time frames than those associated with typical transient stability simulations.
- Combined, items 1 and 2 → Simultaneous simulation of fast and slow dynamics.
- High penetration of PV → Low inertia grid → Increased rate of change of frequency (ROCOF) in response to transient events.

Background and Motivation

- 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 numerical solvers better suited to simulate the fast and slow dynamics over extended time frames associated with a high grid penetration of PV power.

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

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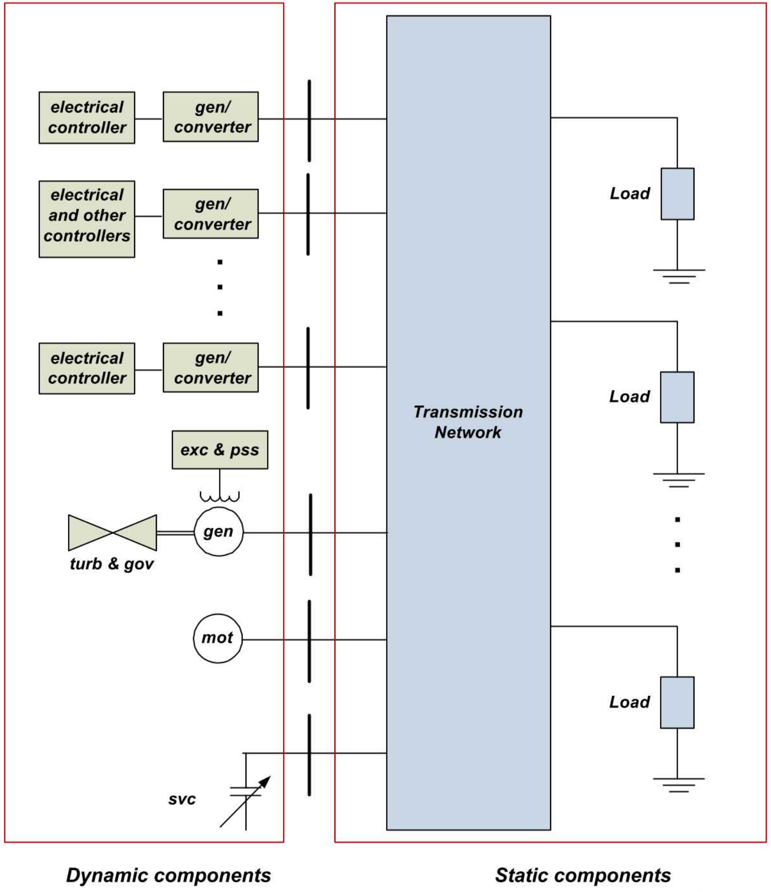
Current Practice

Typical topology of power systems with a high penetration of inverter-connected generation



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Current Practice

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

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

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

where

x: vector of state variables

v: vector of bus voltages (real and imaginary parts)

i: vector of current injections (real and imaginary parts)

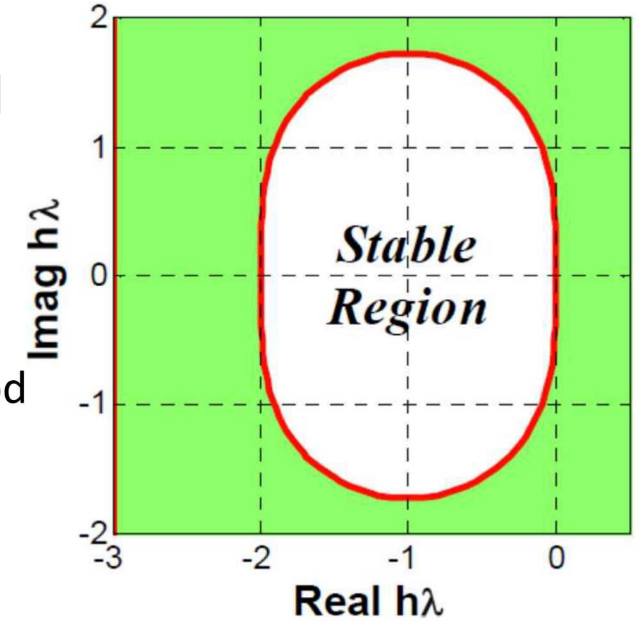
Y: network admittance matrix

Current Practice

- Numerical algorithms for solving equations (1) and (2) compute the state variables and bus voltages at discrete times.
- For the vast majority of transient stability analyses, these times are equally spaced, that is, the integration time step is fixed.
- Typical time domain simulations for power system planning studies covering a time frame spanning 15-30 seconds, will use a fixed integration time step, usually with a value near ¼ cycle = 4.167 ms in a 60 Hz system.

Current Practice: Runge-Kutta Method

The second-order Runge-Kutta (RK2) method is one of the most commonly 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

Plot from: S. Kim and T. J. Overbye, “Optimal Subinterval Selection Approach for Power System Transient S[illegible] Simulation,” *Energies*, vol. 8, pp. 11871-11882, 20[illegible]

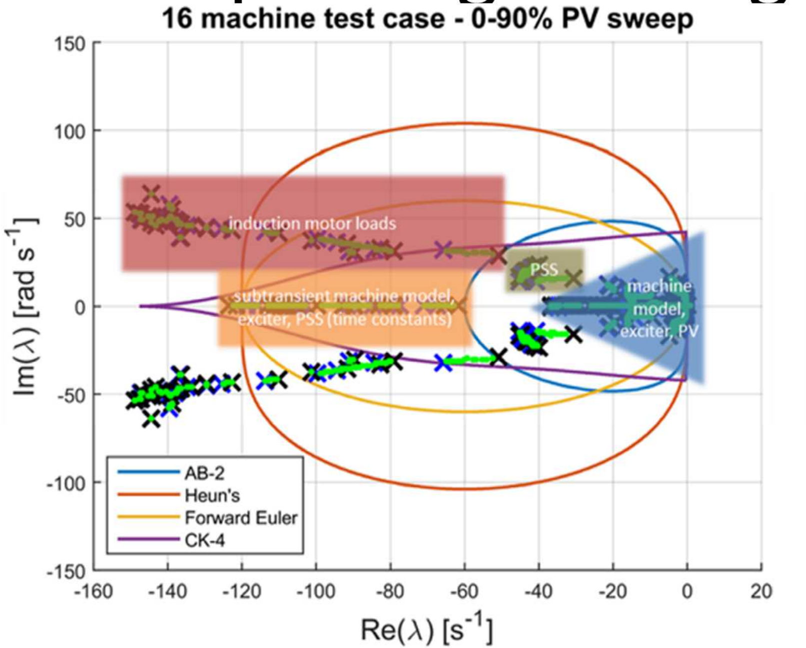
Improving Existing Simulation Capabilities

- Many numerical methods exist for solving sets of ODEs, however the intrinsic properties of large power systems limit the types of numerical algorithms that can be effective in power system dynamics simulations.
- Properties are system size, component diversity and sudden switching events.
- Effective algorithms must:
  - not impose an excessive computational burden
  - provide sufficient accuracy
  - include an efficient adjustment of integration step size
  - allow the use of longer time steps when system is in quasi-steady state

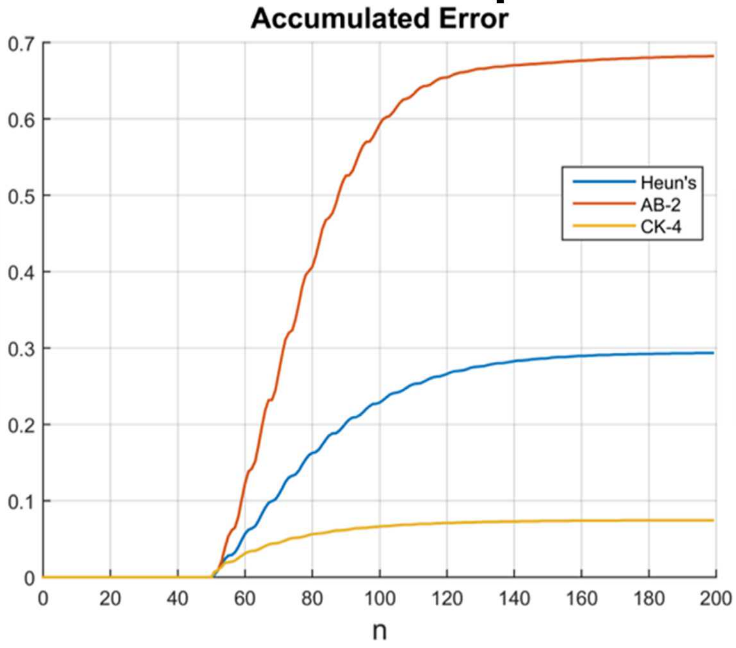
Improving Existing Simulation Capabilities

- With rapid integration of renewables, simulation time frames need to be extended to account for variable PV and wind over long time periods.
- One approach is to use a **variable time step** for integration.
- In this approach, 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

Improving Existing Simulation Capabilities



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

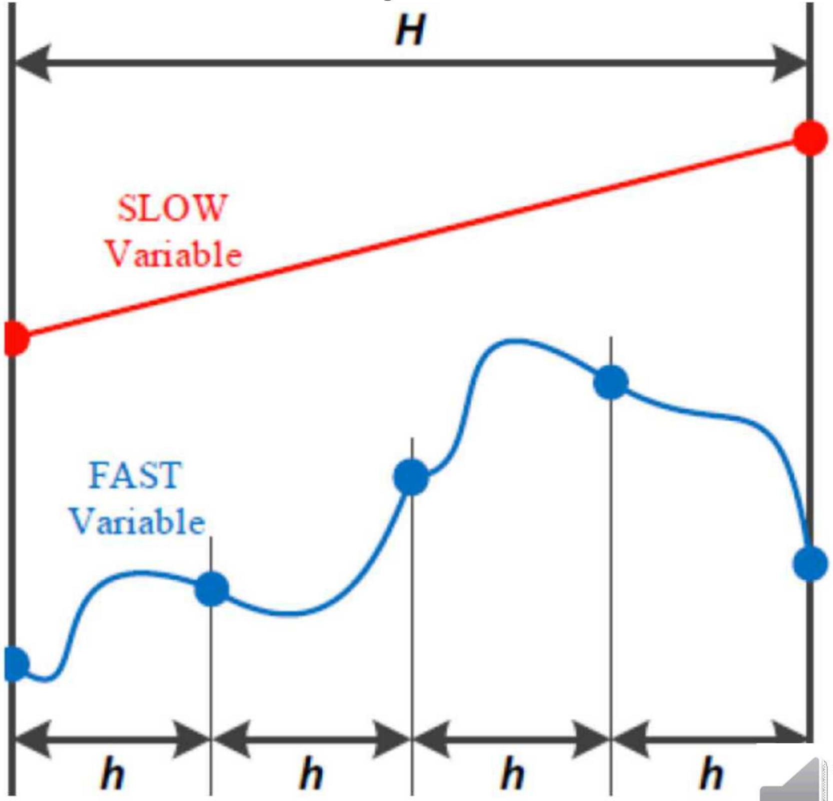


Accumulation of integration error during simulation of a 2nd order ODE with a complex conjugate pole pair.

Plots 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.

Improving Existing Simulation Capabilities

- Another approach to extended simulation times is the use of **multi-rate methods**.
- In this approach, h is a small time step 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.

Improving Existing Simulation Capabilities

- 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 PV power 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.

Acknowledgements

The presenter gratefully acknowledges the support of the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office Award Number DE-EE0036461.

Thank you!

Questions?

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