Efficient Dynamic Security Assessment Under Uncertainties

Amarsagar Reddy Ramapuram Matavalam

Assistant Professor

Arizona State University

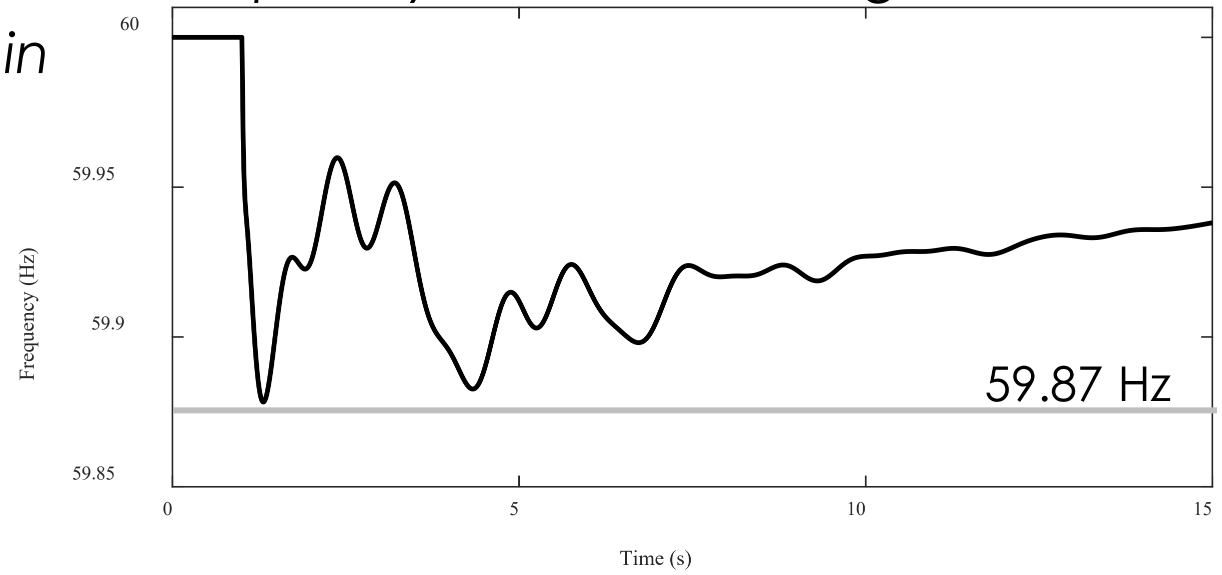
Amar.sagar@asu.edu

Introduction to Dynamic Security Assessment

- Dynamic security assessment (DSA) evaluates a power system's ability to withstand faults/outages and maintain stability during and after the event
- ISO's and utilities simulate many faults at a nominal operating condition and parameter values – offline/day ahead/online

DSA ensures the state trajectory is within pre-specified bounds for system to remain stable and opeartional

Frequency After Gen outage in *WECC 240*



Challenges in DSA due to Uncertainties

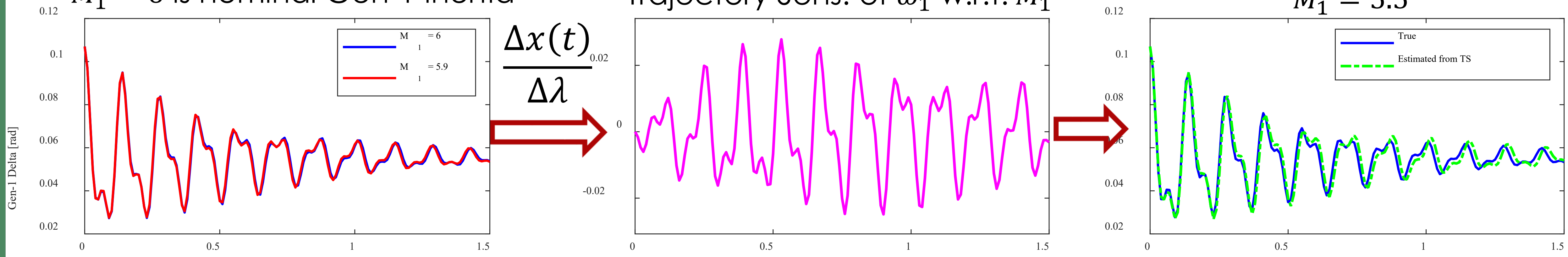
- Uncertainties impact grid dynamic response
  - Uncertain initial condition: fault point-on-wave in EMT
  - Uncertain parameters: $\mathrm{P}_{\mathrm{load}}$, $\mathrm{P}_{\mathrm{gen}}$, other parameters
- Not yet standard in industry – Naive approach is Montecarlo simulation with new parameters
  - Difficult to scale and get insight into the influence of uncertainties
- Polynomial Chaos[1] and Koopman-based methods[2] proposed recently – still need additional simulations

[1] Y. Xu, L. Mili, A. Sandu, M. R. von Spakovsky, and J. Zhao, "Propagating uncertainty in power system dynamic simulations using polynomial chaos," *IEEE Transactions on Power Systems*, vol. 34, no. 1, pp. 338–348, 2018.
[2] **A. R. Ramapuram Matavalam**; U. Vaidya; V. Ajjarapu, "Propagating Uncertainty in Power System Initial Conditions using Data-Driven Linear Operators", in *IEEE Transactions on Power Systems*, 2022.

Approach: Trajectory Sensitivities (TS)

- Captures *sensitivity of trajectories* w.r.t. to parameters & states [3]
  - Linearize along nominal trajectory $x_{\mathrm{nom}}(t)$
  - First-order approx. of $x(t)$ with new param is $x_{updated}(t) = x_{nom}(t) + \Delta\lambda \cdot \mathrm{TS}(t)$

$M_1 = 6$ is nominal Gen-1 inertia — Trajectory Sens. of ω_1 w.r.t. M_1 — $M_1 = 5.5$



- TS is a function of time, state and perturbation
- Better approach to calculate TS?

[3] I. A. Hiskens and M. A. Pai, "Trajectory sensitivity analysis of hybrid systems," in *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications*, vol. 47, no. 2, pp. 204-220, Feb. 2000.

Approach: Efficient Trajectory Sensitivity Calculation

- TS calculated analytically at every time-step from the Jacobian of DAE w.r.t x, y & λ that evolve along trajectory [3]
- Matrix differential equations for $U = \frac{\partial x}{\partial \lambda}$ and $W = \frac{\partial y}{\partial \lambda}$

Power System Equations

$$\dot{x} = F(x, y, \lambda)$$
$$0 = G(x, y, \lambda)$$

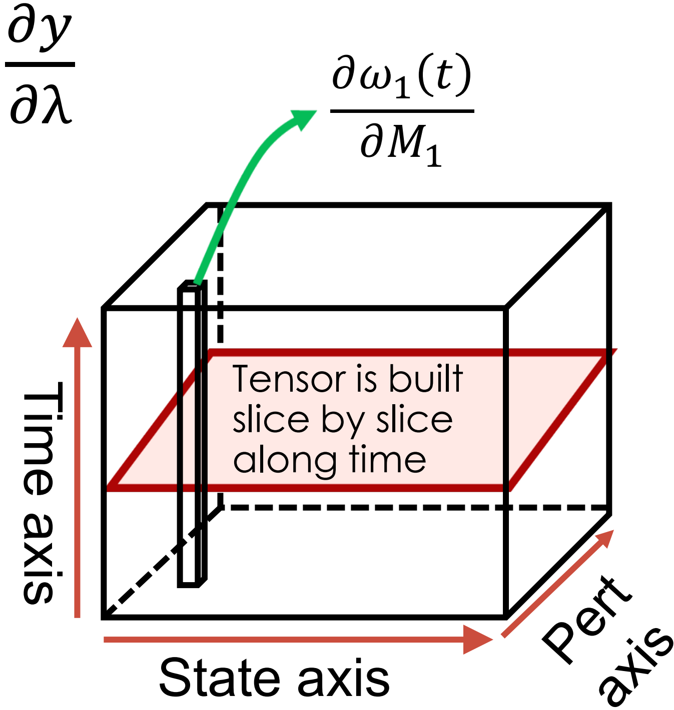
Parameters : λ

EMT simulator: Non-linear DAE

Sensitivity Equations

$$\frac{dU}{dt} = F_x U + F_y W + F_\lambda$$
$$0 = G_x U + G_y W + G_\lambda$$

Time-varying Linear DAE



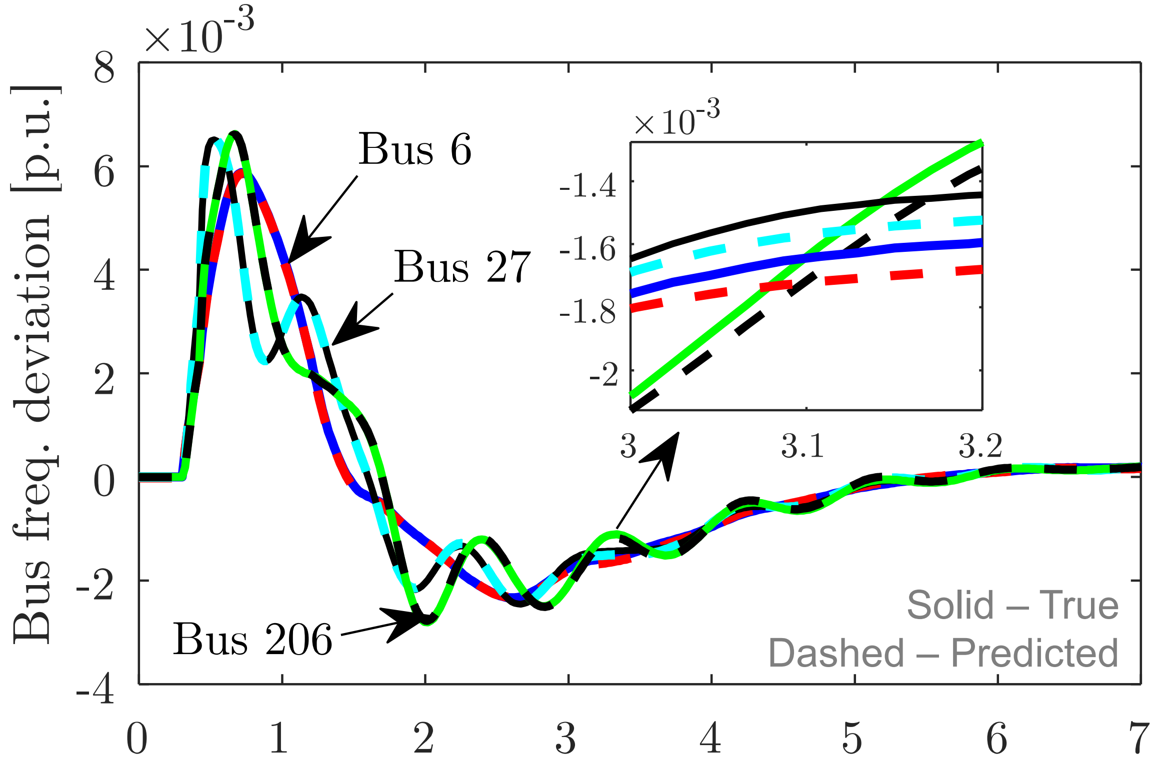
3D - TS at i^{th} time instant for j^{th} state for k^{th} perturbation

Approach: Perturbed Trajectory Calculation

$$x_{updated}(t) = x_{nom}(t) + \sum_{i=1:n_p} \Delta\lambda_i \cdot U_i(t)$$
$$= x_{nom}(t) + U \otimes \boldsymbol{\Delta\lambda}$$

- Handles multiple parametric perturbations
- Efficiently computed using tensor ops
- Tested on WECC-240 bus system with 810 perturbations for bus fault nominal traj.

Parameter Perturbed	Amount
Inertia at 103 machines	+0.1 each
Exciter gain at 103 machines	+10% each
Real power of loads at 139 buses	+3% each
Reactance of 325 HV lines	+5% each
Real power of 140 generators	+3% each
Total number of perturbations	**810**



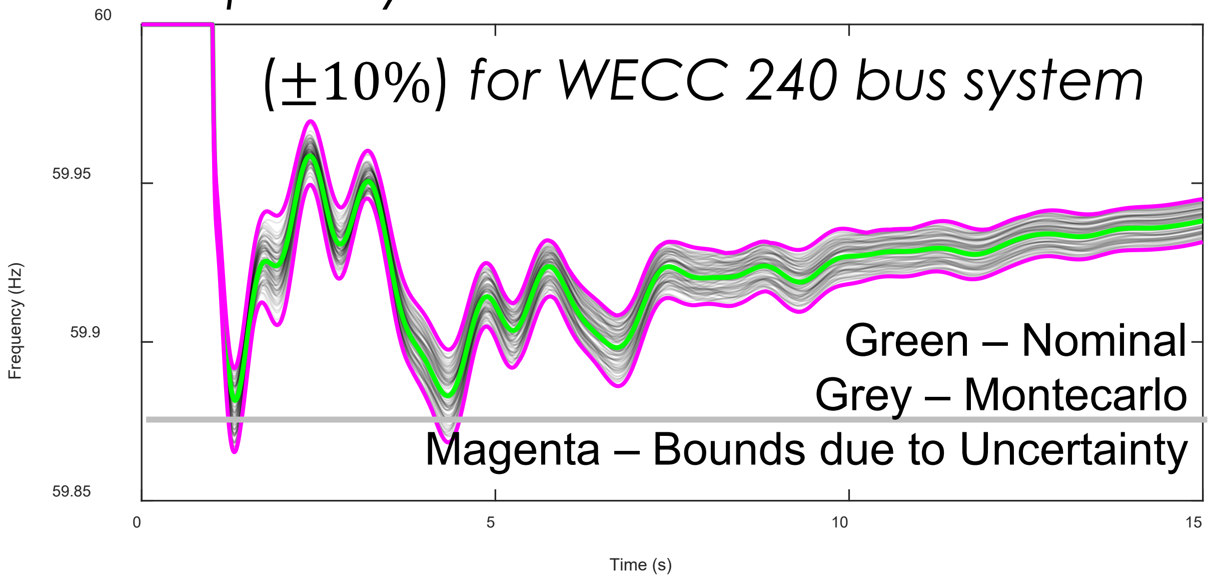
[4] A. Bagga and **A. R. R. Matavalam**, " Tucker Tensor Decomposition of Trajectory Sensitivities for Dynamic Security Assessment," in 2025 IEEE Power & Energy Society General Meeting, Austin, TX, USA, 2025, pp. 1-5

Use Cases – Worst Case Frequency Nadir

- Determine $\Delta\lambda$ that lead to worst case voltage/freq/etc. by formulating a linear optimization problem
- Objective is to minimize updated trajectory: $(x_{nom} + U \otimes \Delta\lambda)$
- Constraints of parametric uncertainty: $\Delta\lambda_{min} \leq \Delta\lambda \leq \Delta\lambda_{max}$
- Max can also be estimated

Enables planners and operators to quantify risk of under-frequency from the frequency bounds

Frequency bounds due to uncertain inertia $(\pm 10\%)$ *for WECC 240 bus system*



Impact

- Efficiently translate parametric bounds to trajectory bounds and find worst case performance without trial and error
  - Estimated bounds from a single nominal simulation
  - >30x faster than Montecarlo
- Systematically identify the most sensitive parameters that impact dynamic performance of the grid
- Only method that can scale to large scale power system DAEs which is precisely what we need in EMT
  - Scales to WECC size systems by exploiting sparsity in Jacobians

Gaps & Challenges Observed

- The DAE of the EMT system model needs to be available along with the Jacobian w.r.t states and parameters
- Switching elements such as MOSFETS, breakers, etc. leads to a more complicated formula for the TS
- Large amount of TS data generated as it adds an extra dimension to the nominal trajectory data
- Second-order TS might be needed if parametric perturbation is large

Next Steps

- Apply TS on EMT DAE to illustrate impact of uncertainty and identify most influential parameters
  - Best to start with simplified dynamical models such as averaged models rather than switching models
- Apply to use cases for DSA under uncertainty
  - Fault Point-on-wave uncertainty
  - Uncertain loads and generators

Thank You for Your Attention

Questions?

Amar.sagar@asu.edu