On Valuing System Inertia and Fast Storage Response

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Project Overview

- Overall objective of project is to determine value of inertia and fast storage response as a grid service.
- #1 - Investigation of inertia's impacts on system primary frequency responses(PFRs) and their locational dependence.
- #2 - Control of fast-acting storage devices (FSDs) to enhance system primary frequency responses.
- #3 - Valuing of virtual inertia services provided by FSDs.

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Milestones and Deliverables

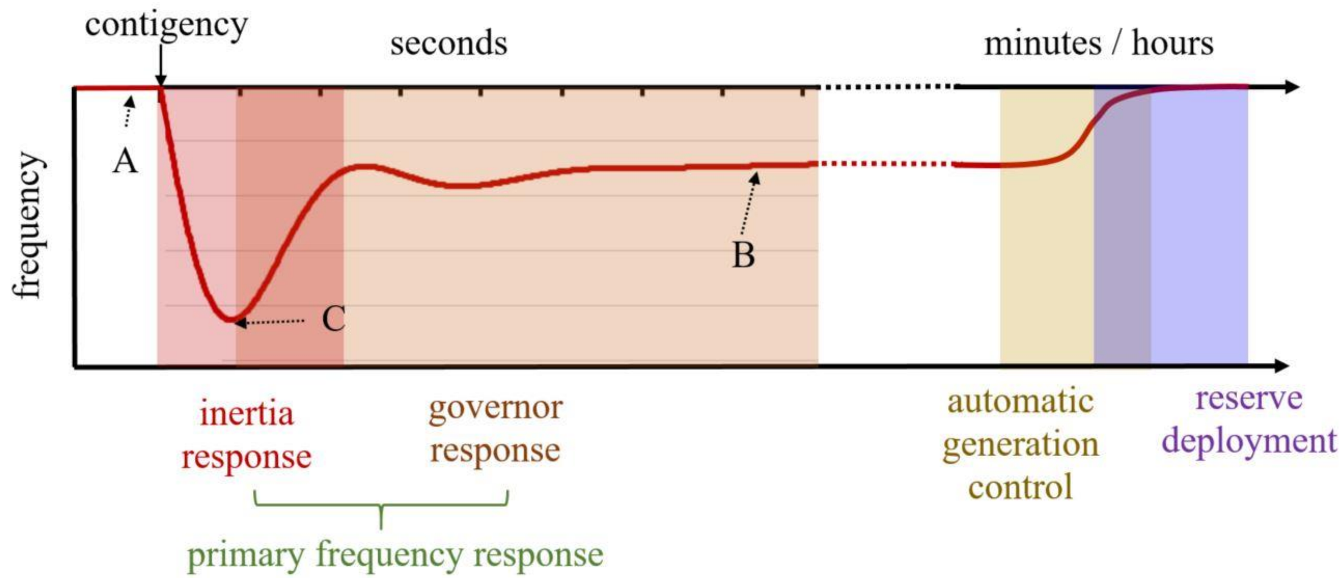
- Create techniques for evaluating the value of system frequency response: #1, #3
- Develop fast analytic sensitivity-based measure: #2
- Demonstrate the techniques using both smaller widely available test systems, and on large models: #1, #2, #3
- Disseminate results in conference and journal papers: #1, #2, #3
- Present at industry events such as PSERC IABs and webinars: #1, #2
- Develop fast analytic assessment method to evaluate the locational impacts of inertial responses: #2, #3

Publications

- T. Xu, W. Jang and T. Overbye, “An Economic Evaluation Tool of Inertia Services for Systems with Integrated Wind Power and Fast-acting Storage Resources”, 49th Hawaii International Conference on System Sciences, Koloa, HI, USA, 2016, pp. 2456-2465
- T. Xu, W. Jang and T. Overbye, "Application of set-theoretic method to assess the locational impacts of virtual inertia services on the primary frequency responses," 2016 IEEE Power and Energy Conference at Illinois (PECI), Urbana, IL, USA, 2016, pp. 1-6.
- T. Xu, W. Jang and T. J. Overbye, "Investigation of inertia's locational impacts on primary frequency response using large-scale synthetic network models," 2017 IEEE Power and Energy Conference at Illinois (PECI), Champaign, IL, USA, 2017, pp. 1-7.
- T. Xu, W. Jang and T. Overbye, "Commitment of Fast-responding Storage Devices to Mimic Inertia for the Enhancement of Primary Frequency Response," under review by IEEE Transaction on Power Systems.

Background

- Imbalance in load and generation may cause frequency excursion and then trigger a sequences of frequency responses that cover multiple time frames:



- Reduction of total system inertia due to integration of light-weight units and renewable resources.

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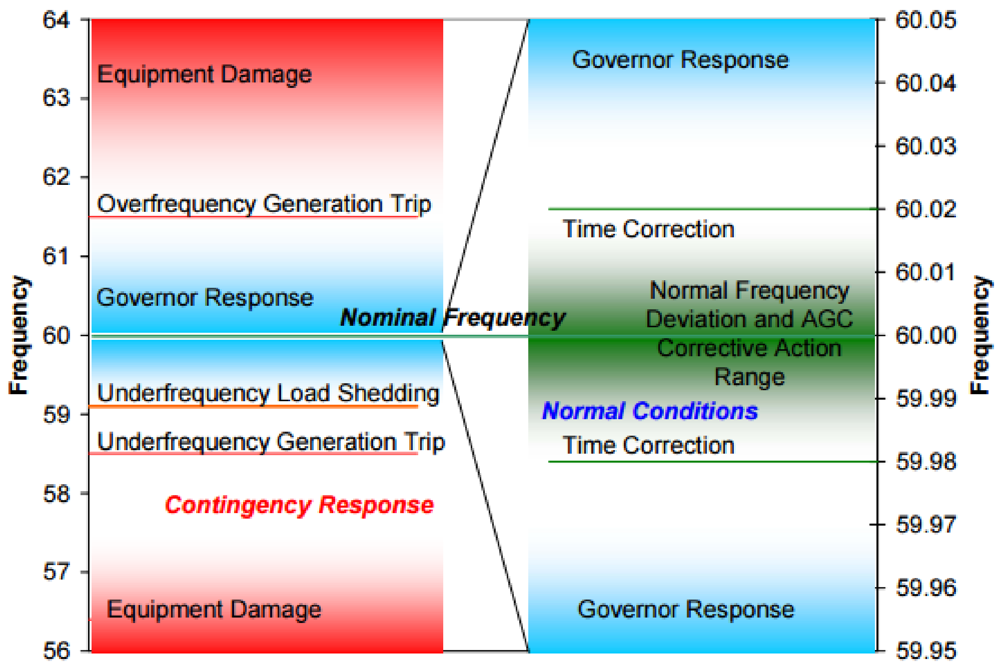
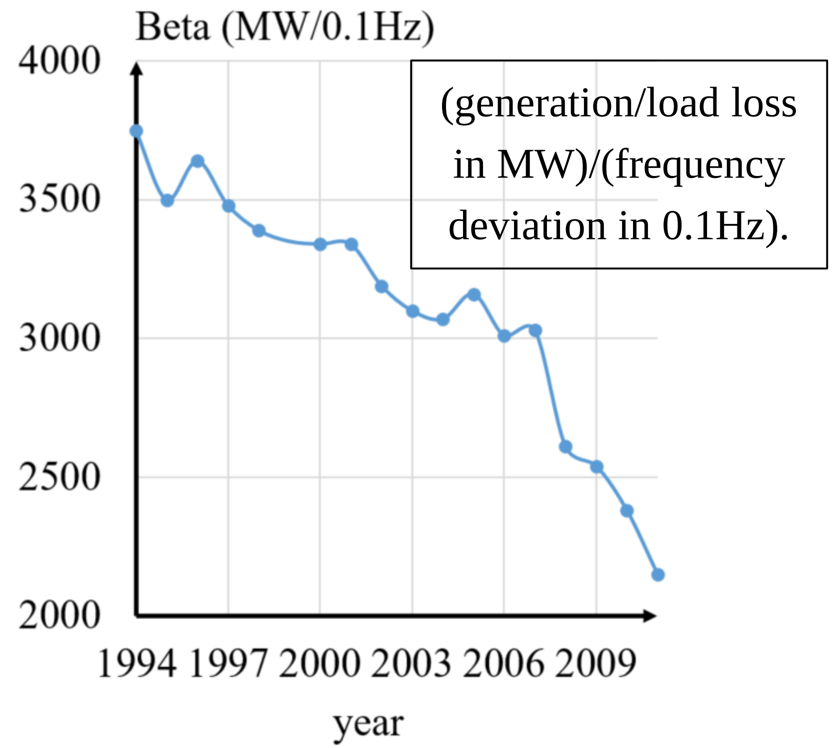
Motivation

- System goal is to maintain frequency within a narrow range





- Declining frequency response in the Eastern Interconnection

Source: http://web.ornl.gov/sci/ees/etsd/pes/pubs/ORNLTM200341.pdf

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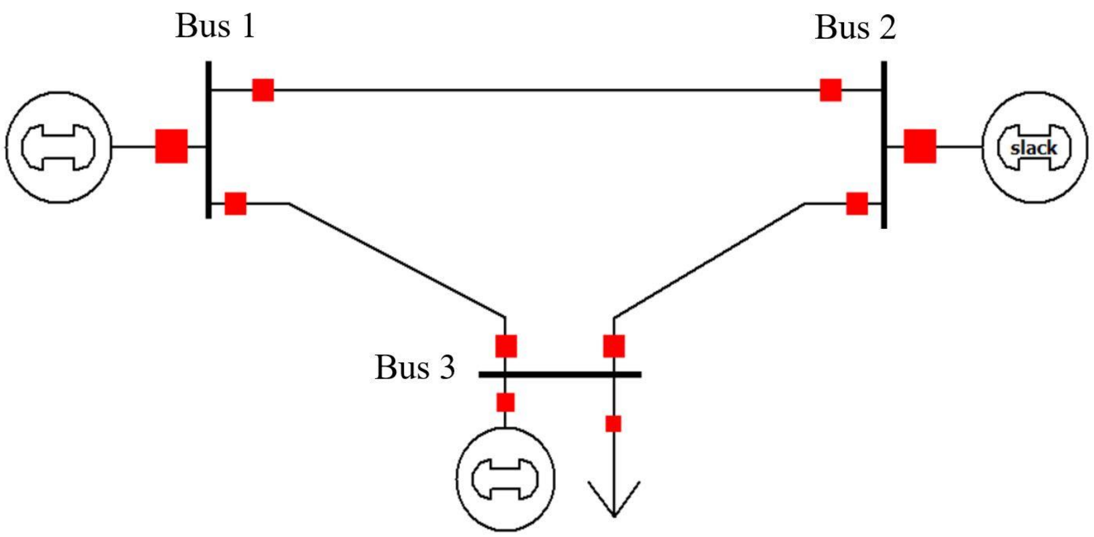
Inertia's Locational Impacts: 3-bus Test Case

- Question: how does inertia impacts system transient stability and whether does inertia location matters?
- This test system supply a load connected to bus 3. Each bus is connected to a generator, modelled with GENCLS (machine) and TGOV1 (governor).



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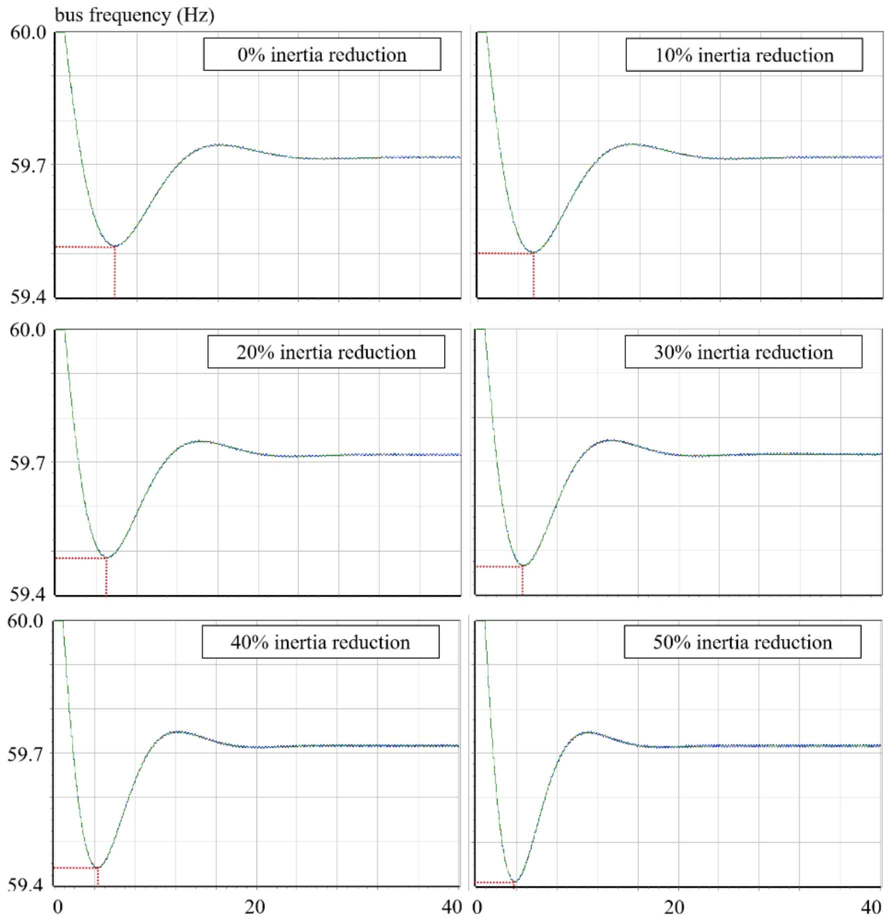
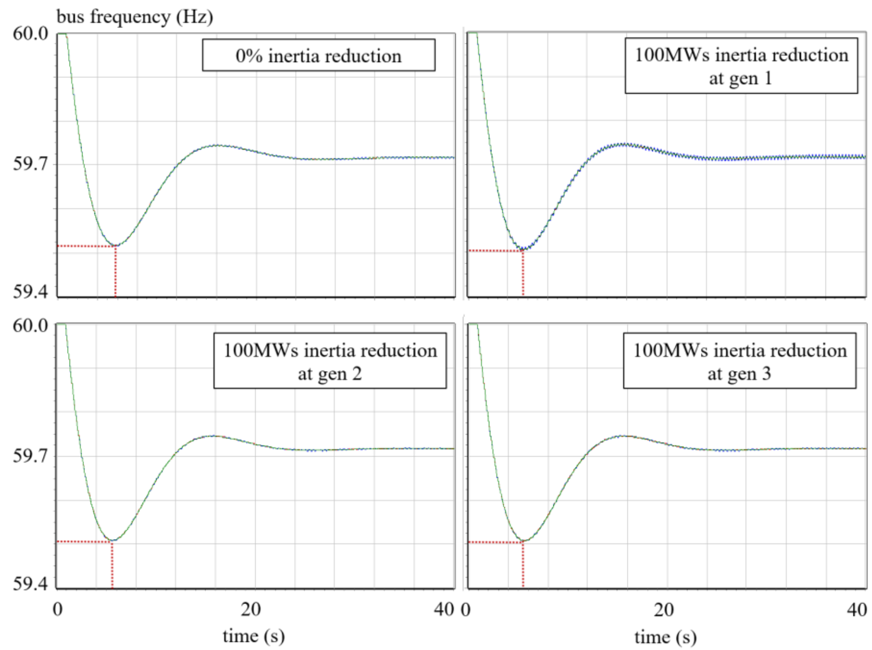
Sudden 10-MW Load Increase



Left: all generators' inertia is reduced by a percentage from 0% to 50% .

Right: 100-MWs inertia is reduced individually at each generator



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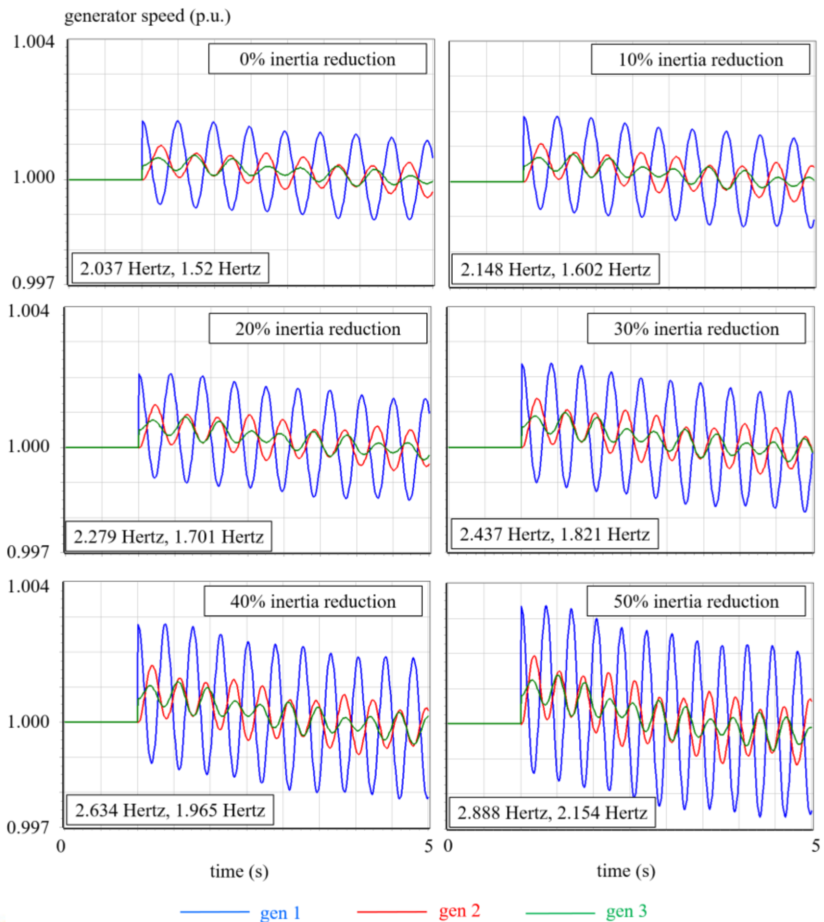
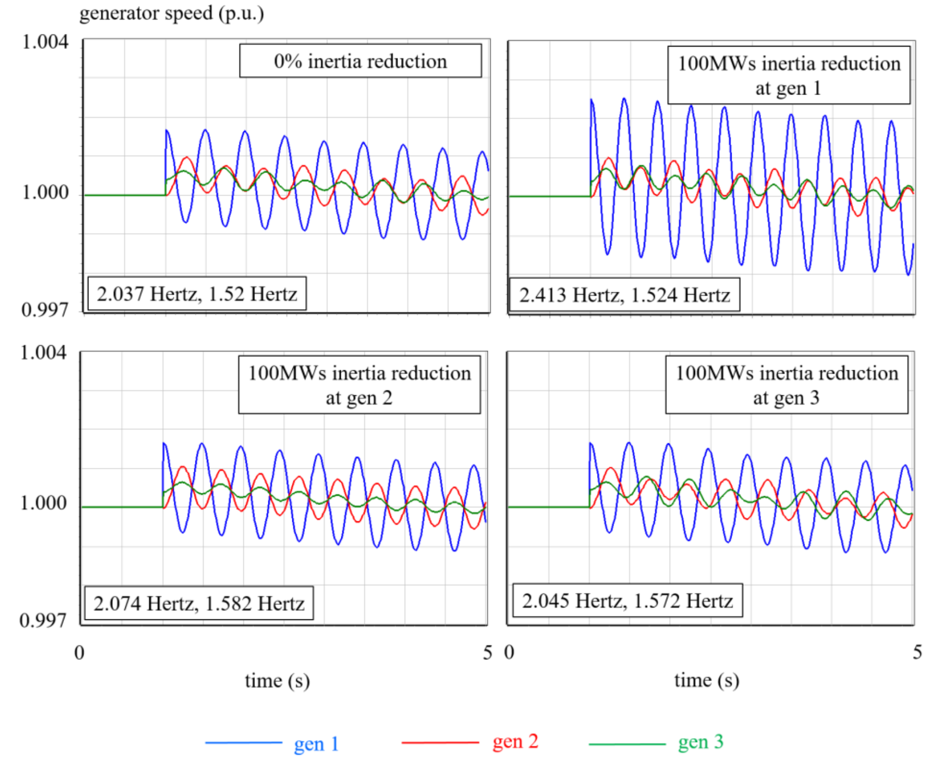
Three-phase Bus Fault Cleared After 0.01s



Left: all generators' inertia is reduced by a percentage from 0% to 50% .

Right: 100-MWs inertia is reduced individually at each generator



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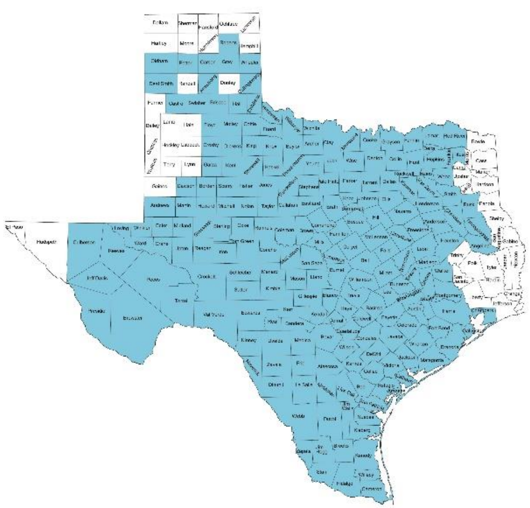
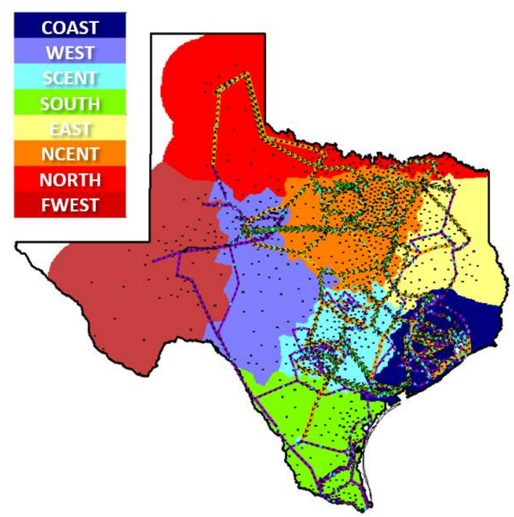
Inertia's Locational Impacts: A Large-scale Synthetic Test Case

- This ACTIVSg2k test case is a 2000-bus power system test case built on the footprint of the Electric Reliability Council of Texas(ERCOT)
- There are three regions with similar total inertia: R1 with COAST (case 1), R2 with SCENT and SOUTH (case 2), and R3 with NORTH, NCENT and FWEST (case 3).





Source: https://electricgrids.engr.tamu.edu/

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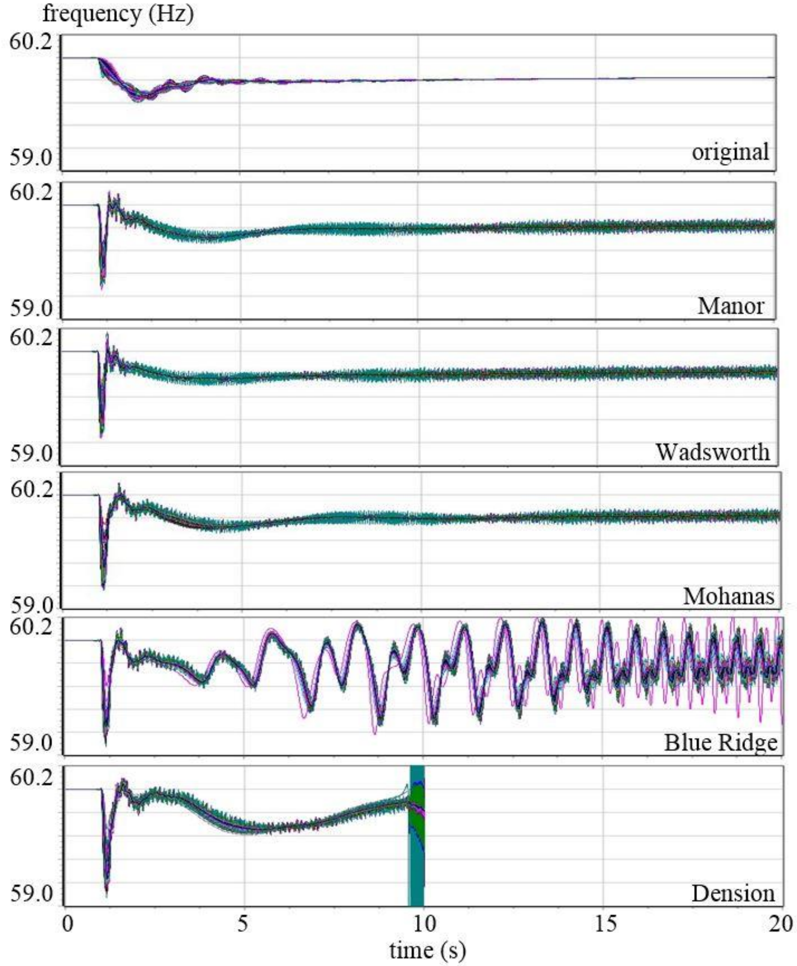
Extreme Case Study

- All resource inertia are located at one site.



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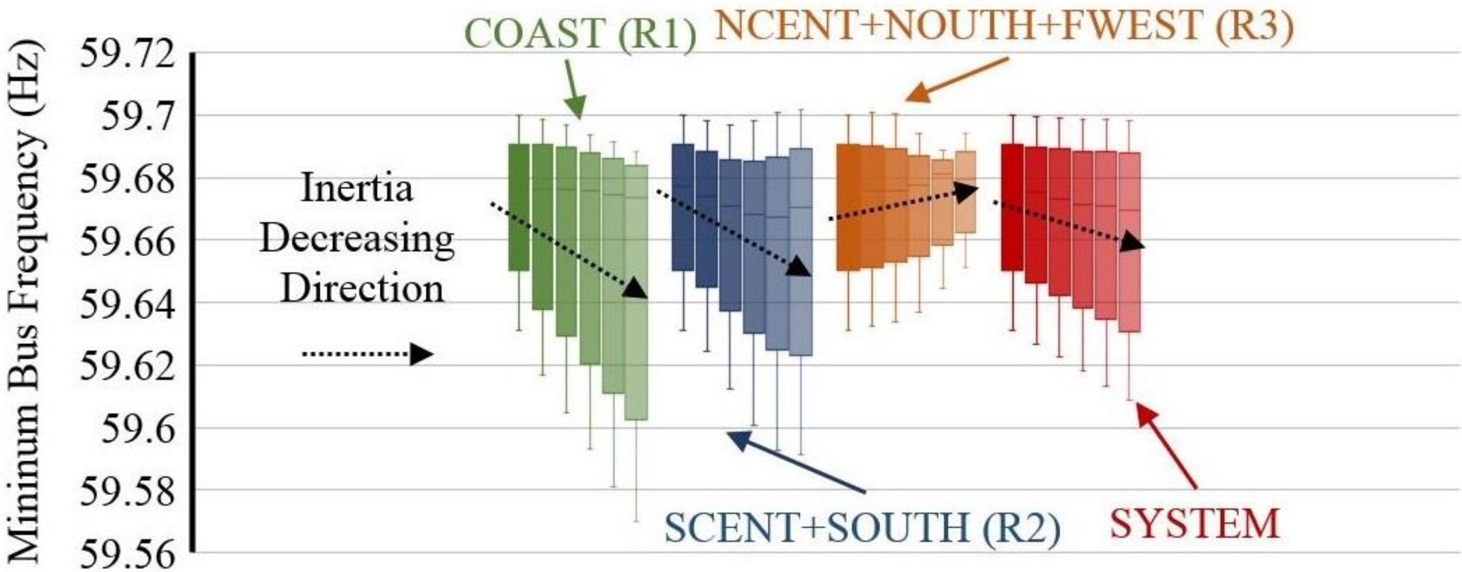
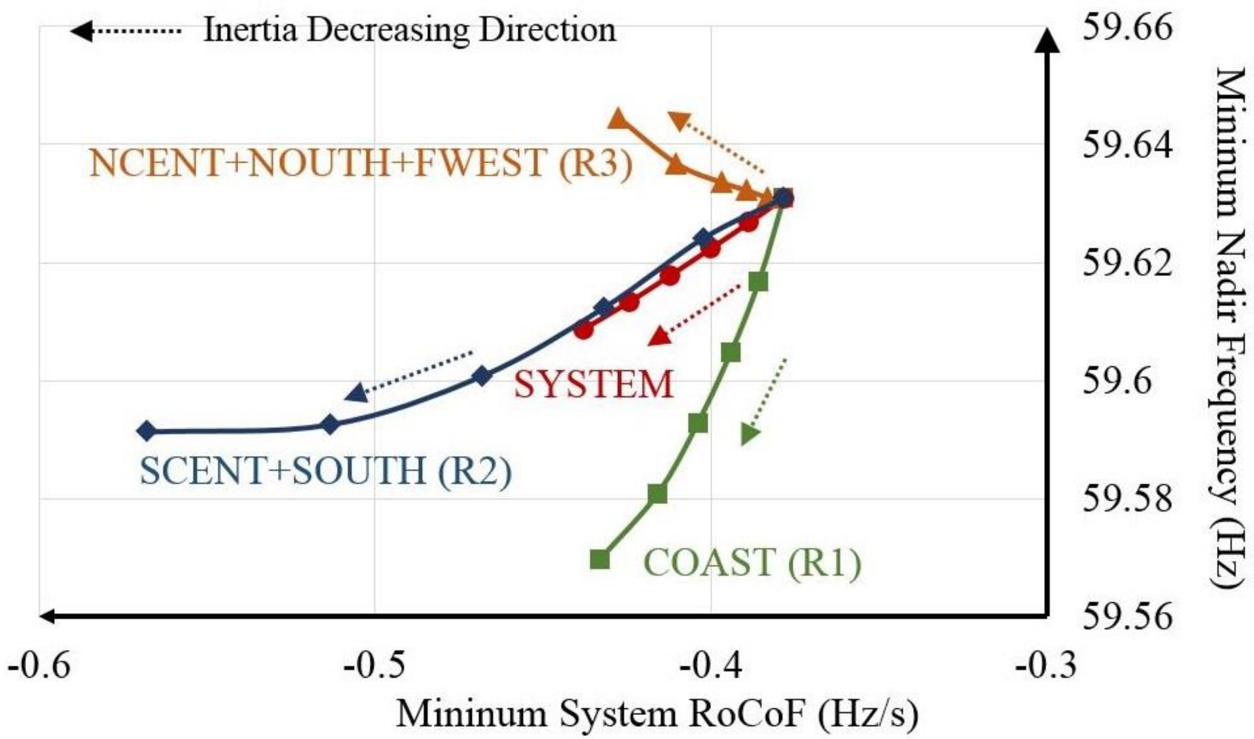
Inertia’s Locational Impacts on Primary Frequency Reponses

- We proportionally reduce inertia of each unit in each region such that the reduction in regional total inertia varies from 0 GWs to 25 GWs in increment of 5 GWs. A contingency with the loss of 2,450-MW generation in R2



Inertia's Locational Impacts on Primary Frequency Reponses

- With the reduction of regional inertia, the minimum rate of change of frequency (RoCoF) decreases correspondingly.



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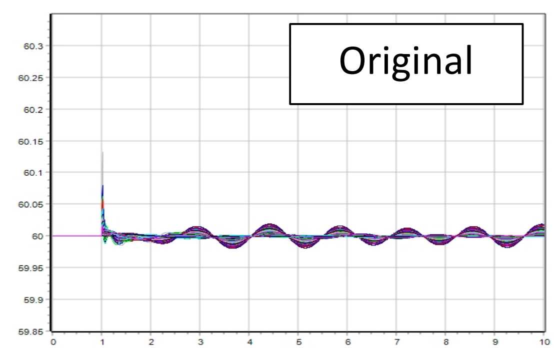
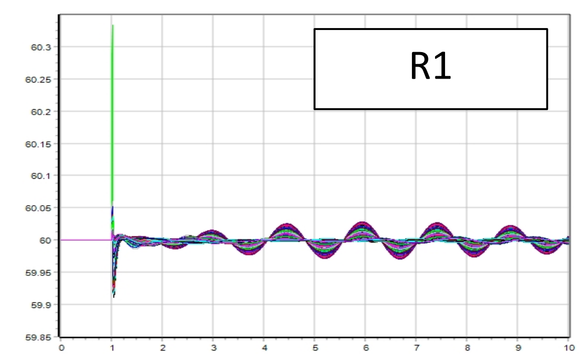
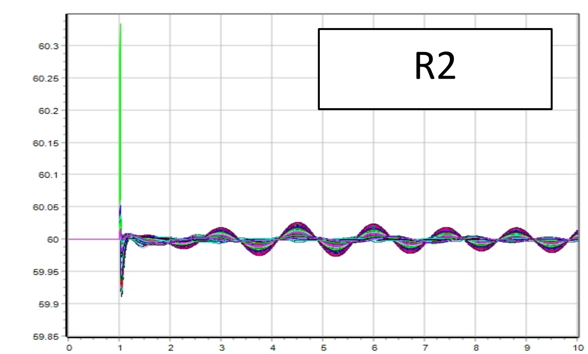
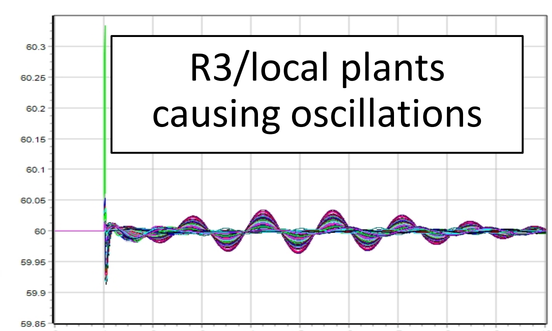
Inertia's Locational Impacts on System Damping Performance

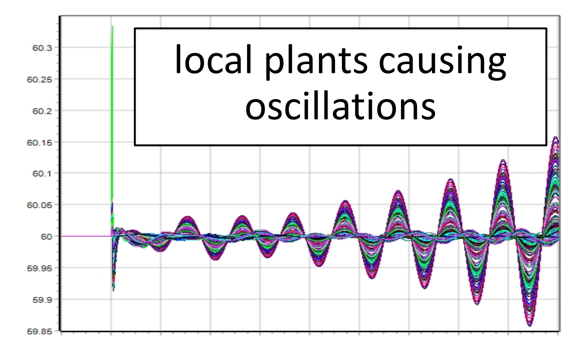
- Natural oscillation (bus fault in R1, local oscillations in R3)
  - Local inertia reduction significantly worsens local oscillation
  - Nearby inertia reduction slightly increases oscillation magnitude











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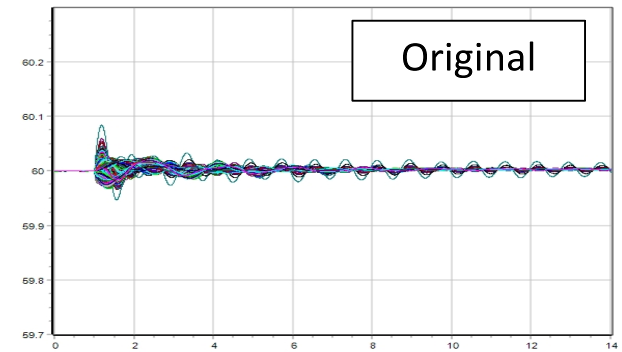
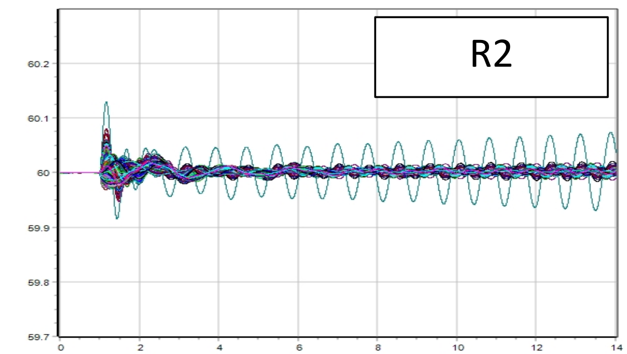
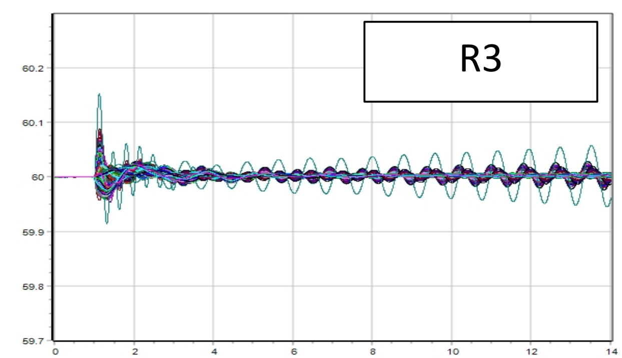
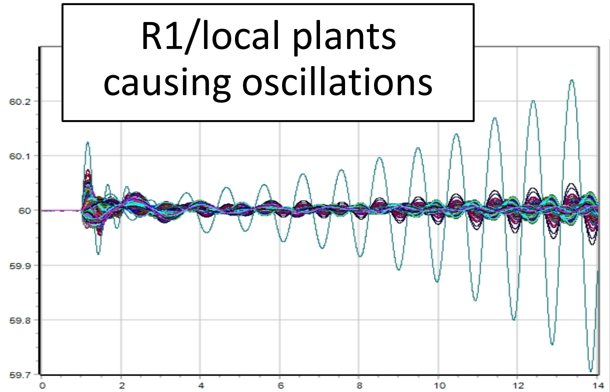
Inertia's Locational Impacts on System Damping Performance

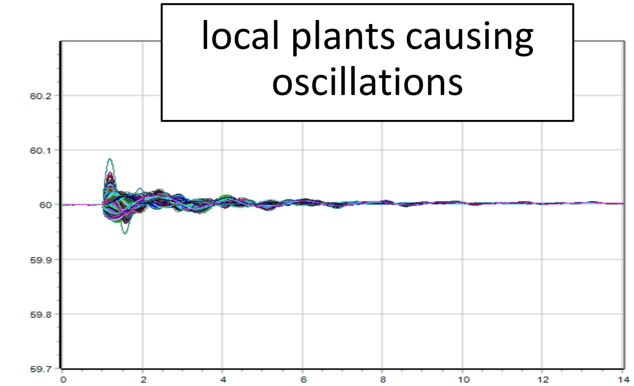
- Natural oscillation (line R2-R3 tripped, local oscillations in R1)
  - Local inertia reduction significantly improves local oscillation
  - Nearby inertia reduction significantly worsens this oscillation











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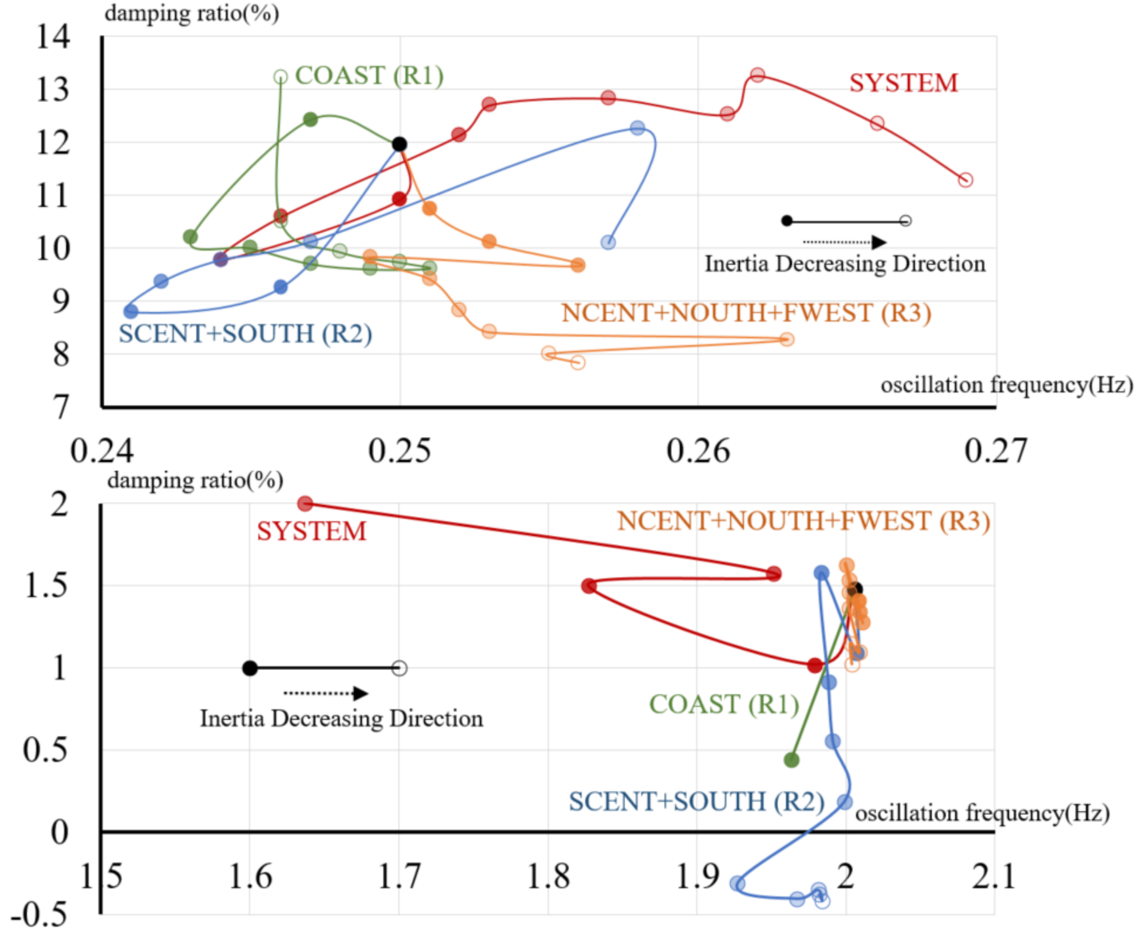
Inertia’s Locational Impacts on System Damping Performance

- 0.5-Hz Forced oscillation in R1 (bus fault in R1)



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Summary and Future Plan on #1

- The locational impacts of inertia on system post-fault electromechanical oscillations and primary frequency responses have been revealed using smaller widely available and large synthetic network cases
- Inertia should be an important factor to be taken into consideration during power system planning, generator siting and other applications related to power system transient stability.
- More simulations under different contingencies are of interest for investigation to study the location-dependent impacts of inertia on power systems

Transient Stability Formulation

- Next, we address the utilization of storage devices as a potential method to provide virtual inertia services into the grid during the system transient processes.
- System transient response over a time period of seconds to perhaps a minute after a contingency could be obtained by solving differential and algebraic equations

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{y}, \mathbf{u})$$
$$\mathbf{0} = \mathbf{g}(\mathbf{x}, \mathbf{y})$$

- For each synchronous machine there are two differential equations, known as the swing equation

$$\frac{d\delta_i}{dt} = \omega_i - \omega_s = \Delta\omega_i$$
$$\boxed{\frac{2H_i}{\omega_s}} \frac{d\omega_i}{dt} = \frac{2H_i}{\omega_s} \frac{d\Delta\omega_i}{dt} = T_{Mi} - T_{Ei} - D_i(\Delta\omega_i)$$

H_i is the inertia constant, with units of seconds

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Virtual Inertial Service Design

- Fast-acting storages (FSDs) are capable to respond up to its maximum charging/discharging rates quickly

$$\Delta\dot{\omega}_i = \frac{p_i^m - [p_i^e - (p^s - p^{s0})]}{2H_i} = \frac{p_i^m - p_i^e}{2H_i + 2H^s}$$

$$E^s = \frac{1}{2} J^s (\omega^s)^2$$

$$H^s = \frac{J^s (\omega_B)^2}{2 S_B r^2}$$

Control Signal

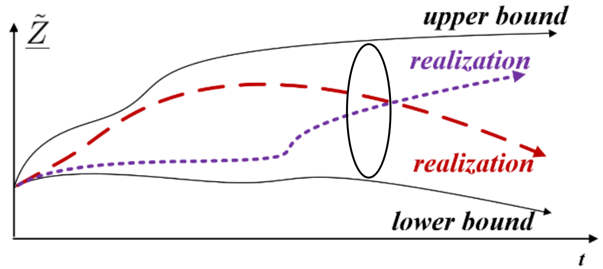
$$\Delta p^s = p^s - p^{s0} = -2H^s \Delta\dot{\omega}_i = -2H^s \dot{\omega}_i$$

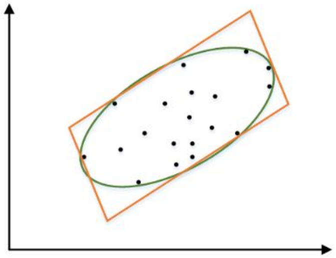
$$\Delta p^s \in [\underline{p}^s - p^{s0}, \bar{p}^s - p^{s0}]$$

$$-\Delta P^s = \dot{E}^s = J^s \omega^s \dot{\omega}^s \Leftrightarrow -\Delta p^s = 2H^s \omega_i \dot{\omega}^i \approx 2H^s \dot{\omega}_i$$

Locational Impacts of Virtual Inertia

- Repeatedly running dynamic simulations is not computationally efficient to determine the unknown but bounded ranges for metrics of interest.





- Both zonotope and ellipsoid can be used to approximate the ranges of the variables and then to estimate the impacts of uncertainty on system dynamic behaviors
- The set $\{\mathcal{U} : \underset{\sim}{\mathbf{u}} \in \mathcal{U}\}$ can be approximated by the set $\mathcal{U} \subset \hat{\mathcal{U}}$, where $\hat{\mathcal{U}}$ is represented by an ellipsoid

$$\mathcal{U} \subset \hat{\mathcal{U}} = \left\{ \mathbf{u} \text{: } (\mathbf{u}\text{-}\mathbf{u}_0)^T \mathbf{F}^{-1} (\mathbf{u}\text{-}\mathbf{u}_0) \right\}$$

Linearized Problem Formulation

- We assume that the variations around the steady-state equilibriums are sufficiently small:

$$\Delta\dot{\mathbf{x}}(t) = \mathbf{A}(t)\Delta\mathbf{x}(t) + \mathbf{B}(t)\Delta\mathbf{u}(t)$$

$$\mathbf{A}(t) = \frac{\partial \mathbf{f}}{\partial \mathbf{x}}|_* - \frac{\partial \mathbf{g}}{\partial \mathbf{y}}|_* \left(\frac{\partial \mathbf{f}}{\partial \mathbf{y}}|_*\right)^{-1} \frac{\partial \mathbf{f}_1}{\partial \mathbf{x}}|_*$$

$$\begin{aligned} \dot{\mathbf{x}} &= \mathbf{f}(\mathbf{x},\mathbf{y},\mathbf{u}) \\ \mathbf{0} &= \mathbf{g}(\mathbf{x},\mathbf{y}) \end{aligned}$$

$$\mathbf{B}(t) = \frac{\partial \mathbf{f}}{\partial \mathbf{u}}|_* - \frac{\partial \mathbf{g}}{\partial \mathbf{y}}|_* \left(\frac{\partial \mathbf{f}}{\partial \mathbf{y}}|_*\right)^{-1} \frac{\partial \mathbf{f}}{\partial \mathbf{u}}|_*$$

- Each ellipsoid $\mathcal{X}_\beta(t)$ for uncertain state variables at time *t* is defined as:

$$\Delta\dot{\mathbf{x}}(t) \in \mathcal{X}_\beta(t) = \left\{\Delta\dot{\mathbf{x}} : \Delta\dot{\mathbf{x}}^T \mathbf{C}_\beta^{-1}(t)\Delta\dot{\mathbf{x}} \le 1\right\}$$

- The propagation rule is set to be:

$$\dot{\mathbf{C}}_\beta(t) = \mathbf{A}(t)\mathbf{C}_\beta(t) + \mathbf{C}_\beta(t)\mathbf{A}^T(t) + \beta\mathbf{C}_\beta(t) + \frac{1}{\beta}\mathbf{B}(t)\mathbf{F}(t)\mathbf{B}^T(t)$$

$$\beta(t) = \sqrt{\frac{tr(\mathbf{C}_\beta^{-1}(t)\mathbf{B}(t)\mathbf{F}(t)\mathbf{B}^T(t))}{N_{\underline{x}}}}$$

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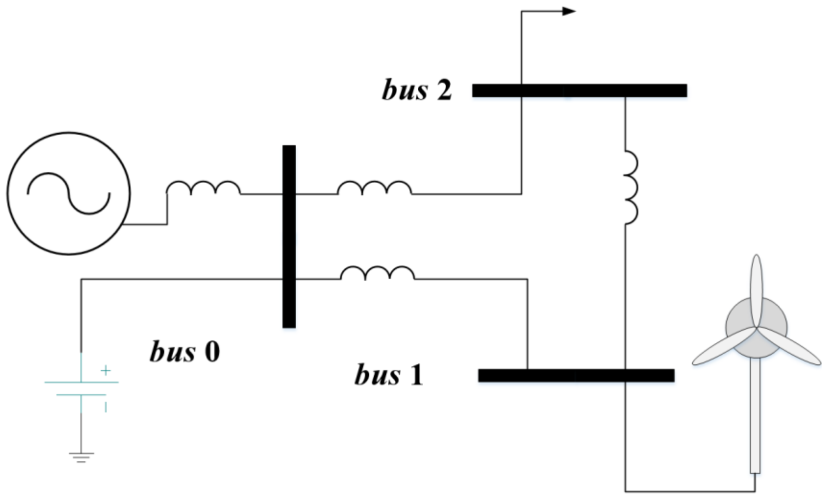
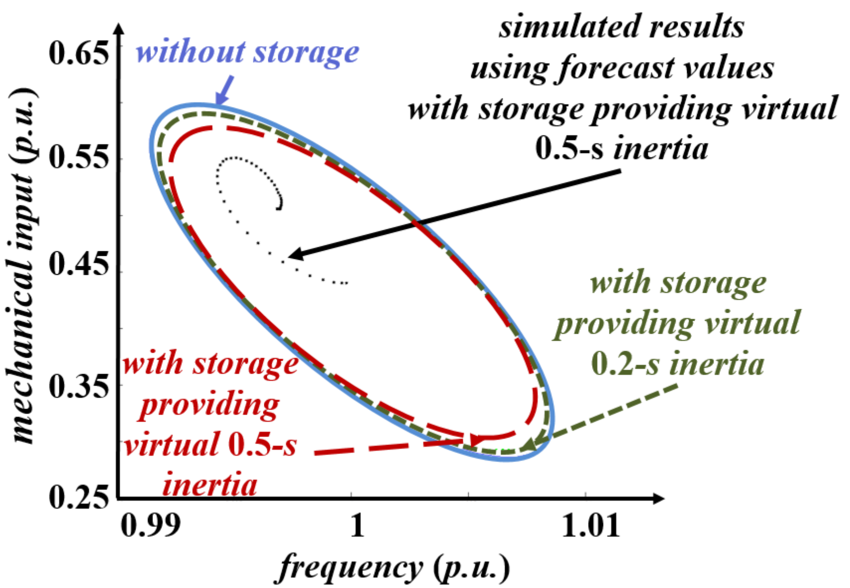
Illustrative Simulation Results

- The three-bus system consists of a synchronous generator connected to bus 0, a renewable-based generating resource connected to bus 1 and a load of 0.7 p.u. (with a 100-MWA base) connected to bus 2.





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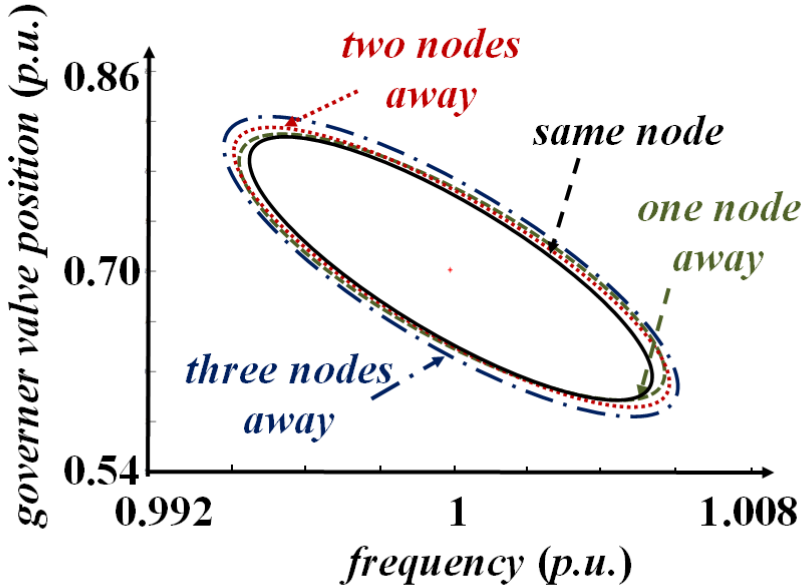
IEEE 24-bus Test System

- We present the computed results for the conventional unit 1 at bus 16 with one single fast-acting storage device of the same configuration installed at site located at the same bus, one bus away (bus 19), two buses away (bus 20) and three buses away (bus 23), respectively



FSD Commitment Problem

- Where to put FSDs and how much virtual inertia to set?
- Given the set $\mathcal{E}$ including *E* contingencies and the marginal costs **c** for virtual inertias **x**, a non-linear scheduling problem for multisite FSDs is formulated to assure that minimum frequency $f_{b,e}^{min}|_{\mathbf{x}}$ and maximum RoCoF magnitude $r_{b,e}^{max}|_{\mathbf{x}}$ of each bus $b \in \mathcal{B}$ for any contingency are within the limits $\underline{f}_b$ and $\bar{r}_b$, respectively:

$$\begin{aligned}
&\min\nolimits_{\mathbf{x}}:\ \mathbf{c}^T\mathbf{x} \\
&s.t.:\ f_{b,e}^{min}|_{\mathbf{x}} \geq \underline{f}_b,\ \text{for } \forall b \in \mathcal{B}, e \in \mathcal{E} \\
&\qquad r_{b,e}^{max}|_{\mathbf{x}} \leq \bar{r}_b,\ \text{for } \forall b \in \mathcal{B}, e \in \mathcal{E} \\
&\qquad x_n \in \{0, [\underline{H}_n, \bar{H}_n]\},\ \text{for } \forall n \in \mathcal{N}
\end{aligned}$$

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Challenges and Solutions

- A search for optimal feasible solutions, with *J* possible values for each FSD, requires O(EJ^N) of full transient stability simulations
- Thus, we develop a sensitivity-based algorithm to effectively solve the optimization problem.

$$
\begin{aligned}
&\min_{\mathbf{d},\mathbf{u}}\text{: } \mathbf{c}^T\mathbf{d} \\
&\quad s.t.\text{:} \quad \text{for } \forall b \in \mathcal{B}, e \in \mathcal{E}, m \in \mathcal{M} \\
&\qquad \sum_{n\in\mathcal{N}, z\in\mathcal{Z}_n} a^m_{b,e,n}[z]|_{\mathbf{H}}(d_{n,z} - \Delta h_{n,z}) \geq v^m_{b,e}|_{\mathbf{H}} \\
&\qquad u_{n,z} \in \{0,1\} \\
&\qquad \text{for } \forall b \in \mathcal{B}, e \in \mathcal{E}, z \in \mathcal{Z}_n, n \in \mathcal{N} \\
&\qquad d_{n,z} \leq u_{n,z}(h_{n,z} - h_{n,z-1}) \\
&\qquad u_{n,0}h_{n,0} \leq d_{n,0} \\
&\qquad u_{n,z+1}(h_{n,z} - h_{n,z-1}) \leq d_{n,z}, \quad z \neq \bar{Z}_n
\end{aligned}
$$

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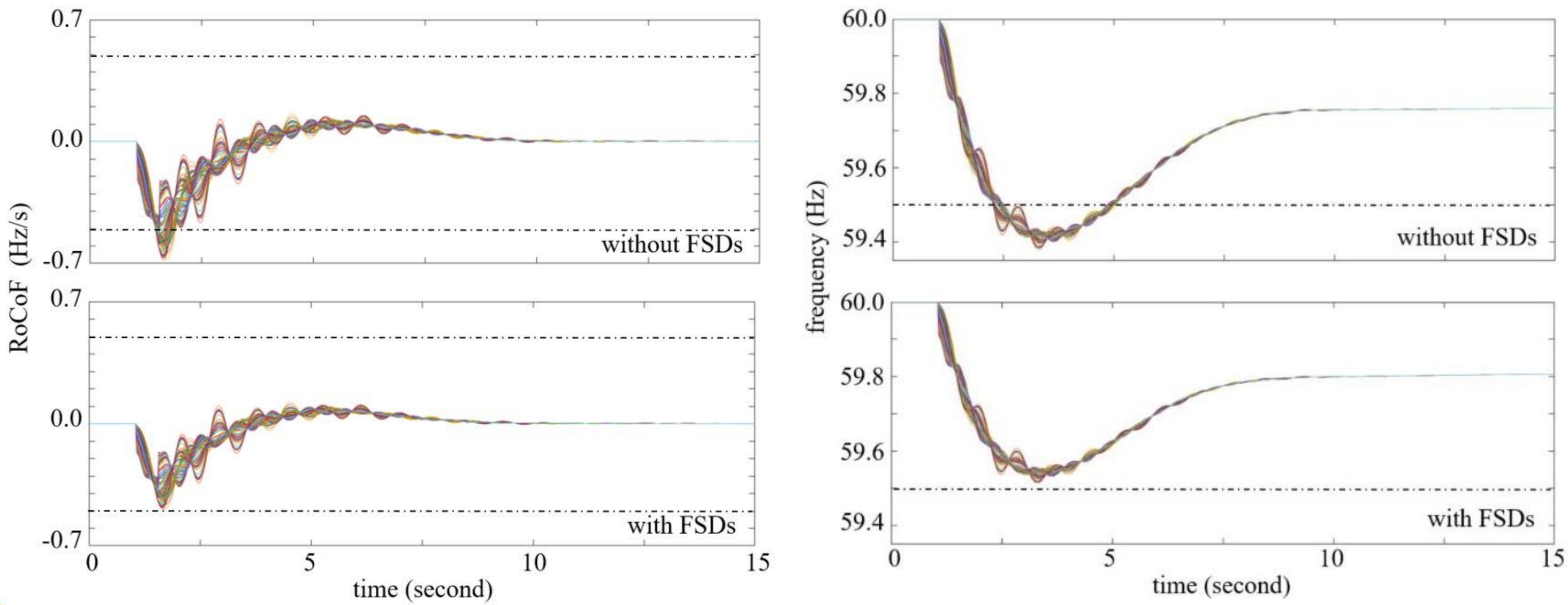
Illustrative Simulation Results

- The proposed algorithm can find a near-optimal solution (difference less than 0.4%) for a 118-bus test system, while requiring ~800 full dynamic simulations, compared to the generic method (~15000 full dynamic simulations)



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Summary and Future Plan on #2

- A dynamic model for grid-connected storage systems has been considered in this work.
- An iterative, sensitivity-based method has been proposed to effectively finding the near-optimal commitment of FSDs with significant reductions in computational complexity.
- Once an improved storage dynamic model is developed, contribution of virtual inertia provided by FSDs to enhance system PFR and damping performances will be studies on larger-scale cases. Droop controls for FSDs will be also considered.

Valuing of Virtual Inertia Services

- We base on the security-constrained unit commitment (SCUC) model to develop an approach to assess the economic value of virtual inertia service.
- The nonlinear constraints results in computational burdens; some of physical constraints cannot even be directly represented in an optimization problem.

$$\min_{x,u} \quad C_x^T x + C_u^T u$$
$$s.t. \quad Ax + Bu \le e$$
$$u \in \{0,1\}^{|u|}$$

$$z(0) = Dx$$

$$E(u)\dot{z} = F(u)z + Gv$$
$$z \in [\underline{z}, \overline{z}]^{|z|}$$

Valuing of Virtual Inertia Services

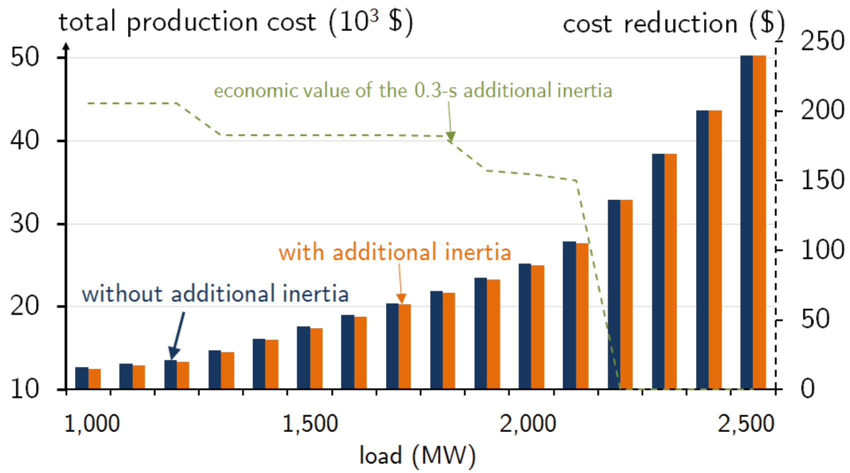
- We deal with those challenges by:
  - Discretizing the dynamic simulation model;
  - Integrating discrete-time dynamic simulation model into steady-state unit commitment model as security constraints;
  - Transforming nonlinear constraints into equivalent linear forms.

$$\begin{aligned} \min_{x,u} \quad & C_x^T x + C_u^T u \\ s.t. \quad & Ax + Bu \le e \\ & u \in \{0,1\}^{|u|} \end{aligned}$$

$$\hat{z}[0] = Dx$$

$$\begin{aligned} & E' u + E'' \hat{z}[\cdot] \\ & = F' u + F'' \hat{z}[\cdot] + Gv \end{aligned}$$

IEEE 24-bus Test System



- Introduction of additional inertia service
  - Total production cost is reduced
  - No need to require more units online to maintain the post-contingency frequency within its limits
- As load level goes higher
  - More units to be online with higher total system inertia value
  - Less need of additional inertia to resist frequency deviation after contingency

Summary and Future Plan on #3

- We modified the security-constrained unit commitment framework for the effective integration of dynamic performance constraints.
- A trade-off between energy and ancillary services requires a market simulation framework, which completes the power market clearing process and considers the transient stability constraints.
- A sensitivity-based method is of need to improve the computational effectiveness.
-

Q&A

- Thanks!