CERTS Meeting

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On Valuing System Inertia and Fast Storage Response

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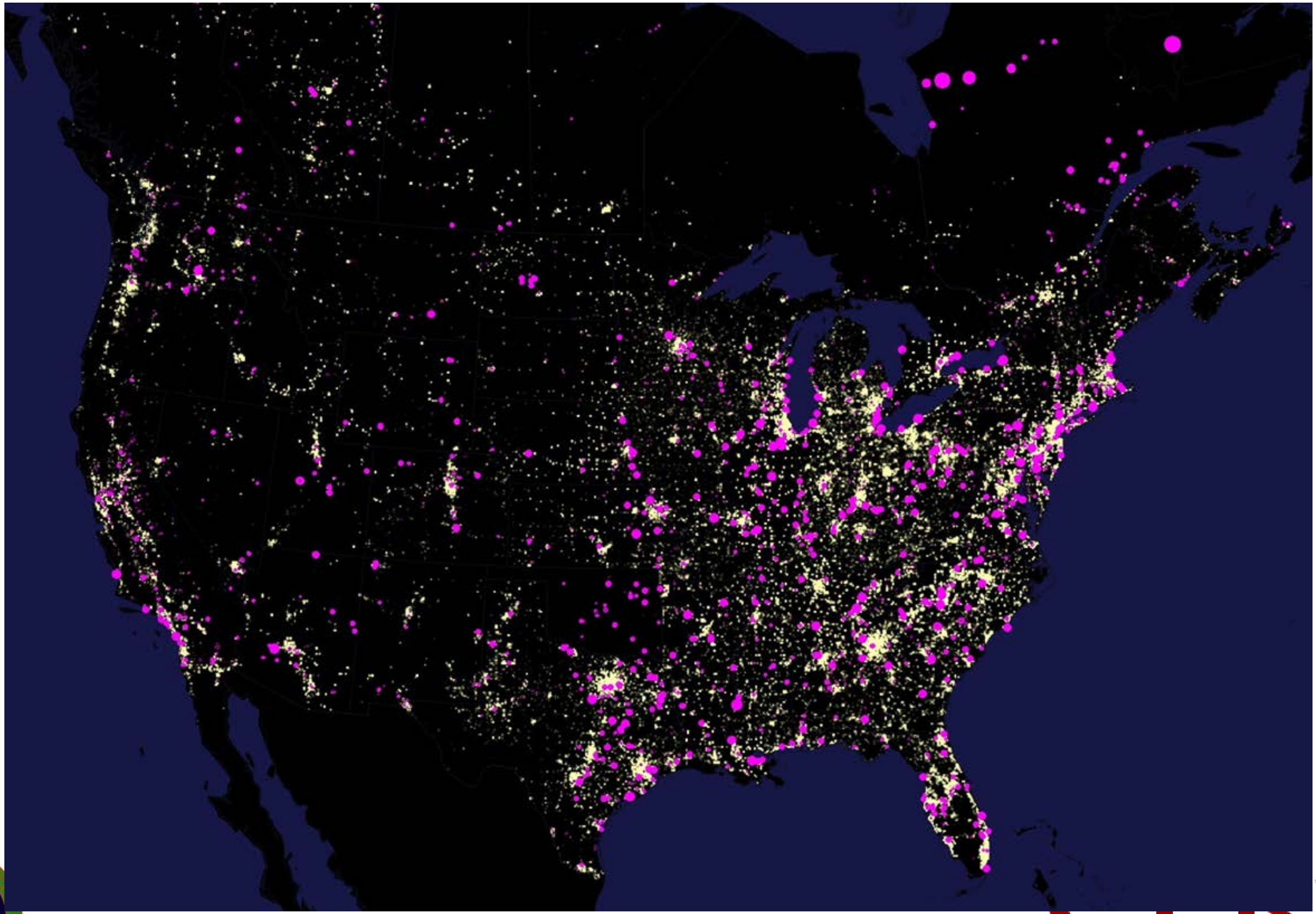
Overview

- Overall objective of project is to determine the value of inertia and fast storage response as a grid service
- Grid is changing due to the deployment of more generation with little or no inherent inertia
- System goal is to maintain frequency within a relatively narrow range
- The value of a resource will be related to its ability to provide an improvement in the frequency response

North American Electric Grid



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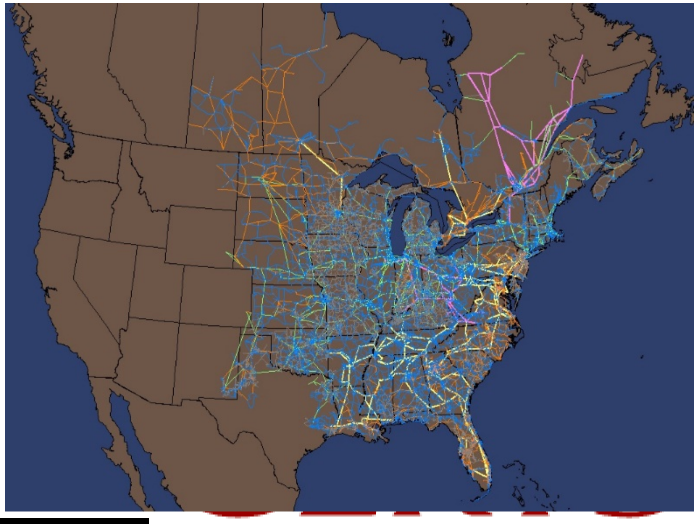
Previous Work: Determining Equivalent Line Limits

- Overall objective
  - To develop equivalent systems that preserve desired attributes of the original system
- Focus this year
  - To create equivalents of interconnection level power grids that preserve line limits
- Special emphasis
  - To apply algorithm to a “backbone” type equivalent of large systems such as Eastern Interconnection (EI)
  - Key result is limits have been assigned to the EI equivalent provided by the Tylavsky group

Previous Work: Determining Equivalent Line Limits

- Previous years
  - Developed equivalent line limit theory – exact values are not always possible
  - Developed initial algorithms for bounding limits (Hungarian method, Quadratic programming)
  - Both worked well only for small systems due to computational burden (applied to IEEE 118-bus case)
- 2014 meeting
  - Third method, Top-down approach was developed
  - Applied to backbone-type Eastern Interconnection case 62,000 to 5,200 buses



Previous Work: Determining Equivalent Line Limits

- Criteria of method
  - Maintaining total transfer capability (TTC) of bus pairs of equivalent lines for the same pairs in the full case
- Biggest issue was large TTC mismatches
  - About 1,400 negative reactance lines in the full case provided excessive PTDFs that resulted in inaccurate equivalent line limits
    - 11 lines from already existing equivalent lines in the case
    - About 1300 branches from three-winding transformers
- Solved with Wye-delta conversion
  - Converted about 1000 negative reactance transformer branches to positive ones

Previous Work: Determining Equivalent Line Limits

- Top-down method providing lower bounds
  - Even though the algorithm calculates best estimates, in small cases it provides similar or same limit values to lower estimates from Max/Hungarian method
- EI case with upper limits assigned
  - Modified the upper limit calculation of Max/Hungarian method to be applicable to large-scale systems
  - Sub-group elimination used for faster computation
    - 2388 sub-groups of external buses
    - Biggest sub-group: 43351 buses and 1414 first neighbor buses

Previous Work: Determining Equivalent Line Limits

- Improved algorithms with less TTC mismatch
- EI case now assigned with best estimates and upper estimates
  - Best estimates have only 3.8% of average TTC mismatch for all equivalent lines after getting rid of impacts from negative reactance lines
  - Upper estimates have 34% higher average equivalent line limits than best estimates
  - Upper estimates have also higher average TTC mismatches of 32%
- Both applicable to any other large-scale cases

Inertia Project Background: Power System Time Scales

- Project focuses on the transient stability time scale

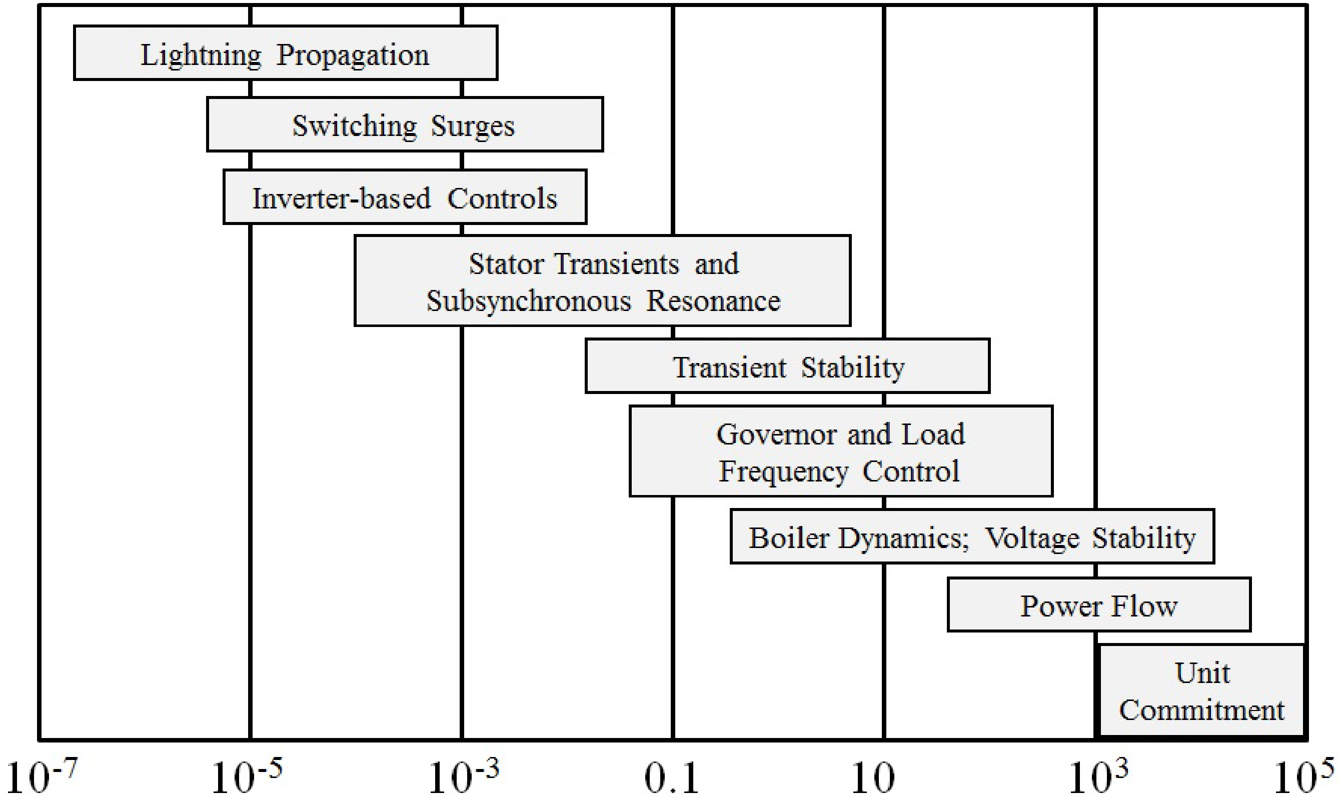


Image source: P.W. Sauer, M.A. Pai, Power System Dynamics and Stability, 1997, Fig 1.2, modified

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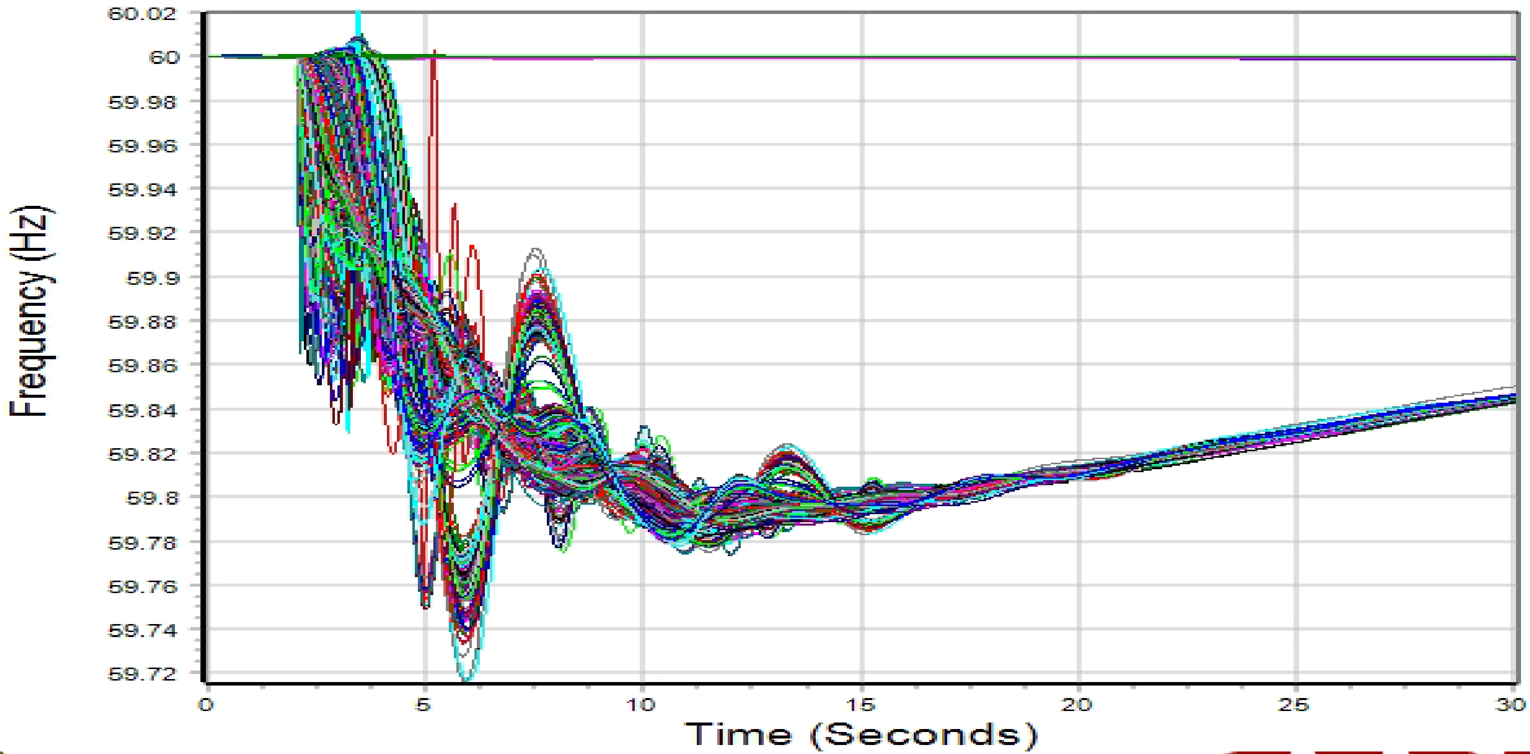
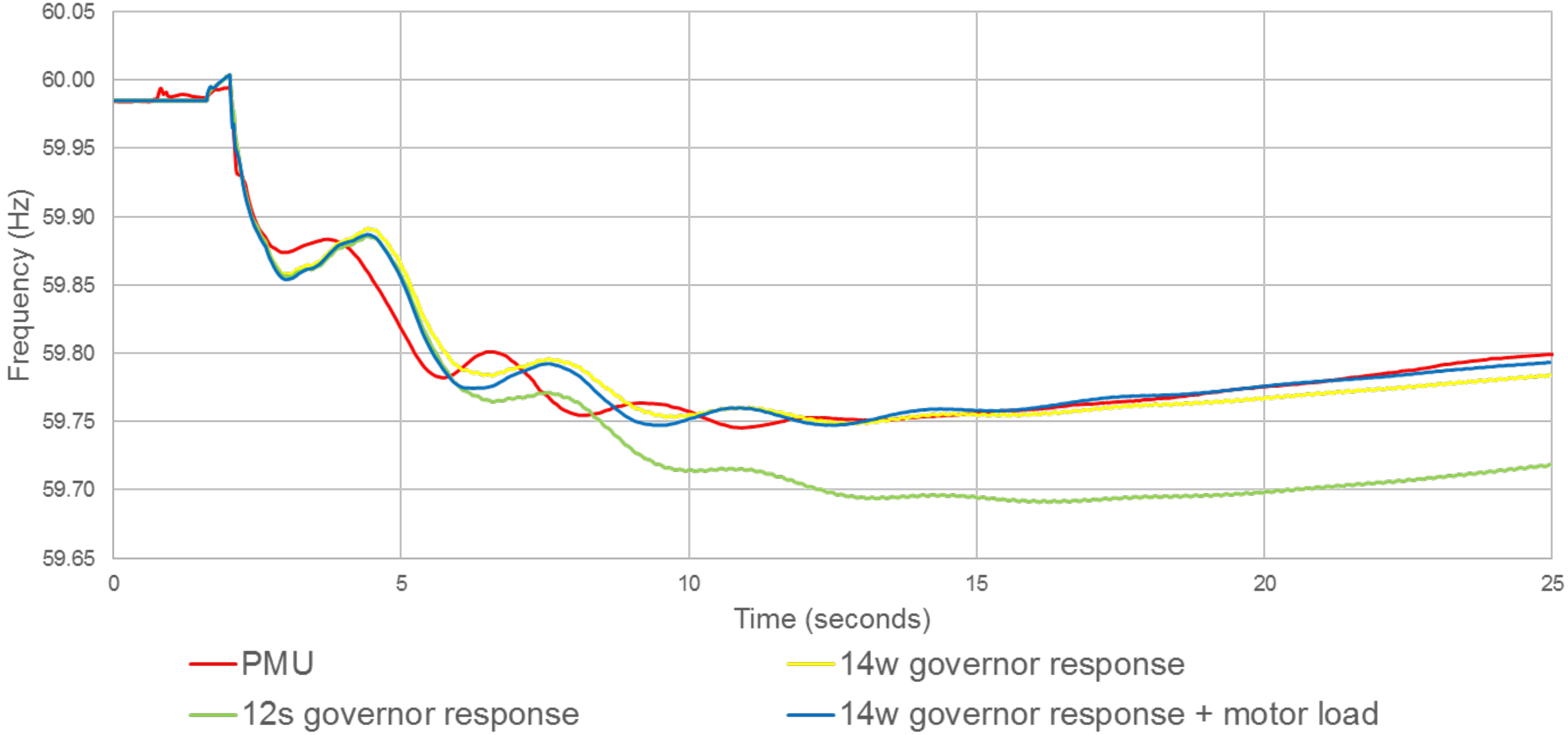
Example Transient Stability Results

- Figure shows simulated generator frequencies after a large generator outage contingency



Actual Event Validation

➢ Figure compares the pmu results for an actual event to three modeled values



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Transient Stability Formulation

- Goal is to determine response of system over a time period of seconds to perhaps a minute after a contingency
- General form of the problem is solving

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

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

where $\mathbf{x}$ is the vector of the state variables, $\mathbf{y}$ is the vector of the algebraic variables (primarily the bus complex voltages), and $\mathbf{u}$ is the vector of controls

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Transient Stability Solution and the Swing Equation

- The differential and algebraic equations (DAEs) can be integrated using either explicit or implicit methods
- For each synchronous machine there are two differential equations, known as the swing equation

$$\frac{d\delta_i}{dt} = \omega_i - \omega_s = \Delta\omega_i$$

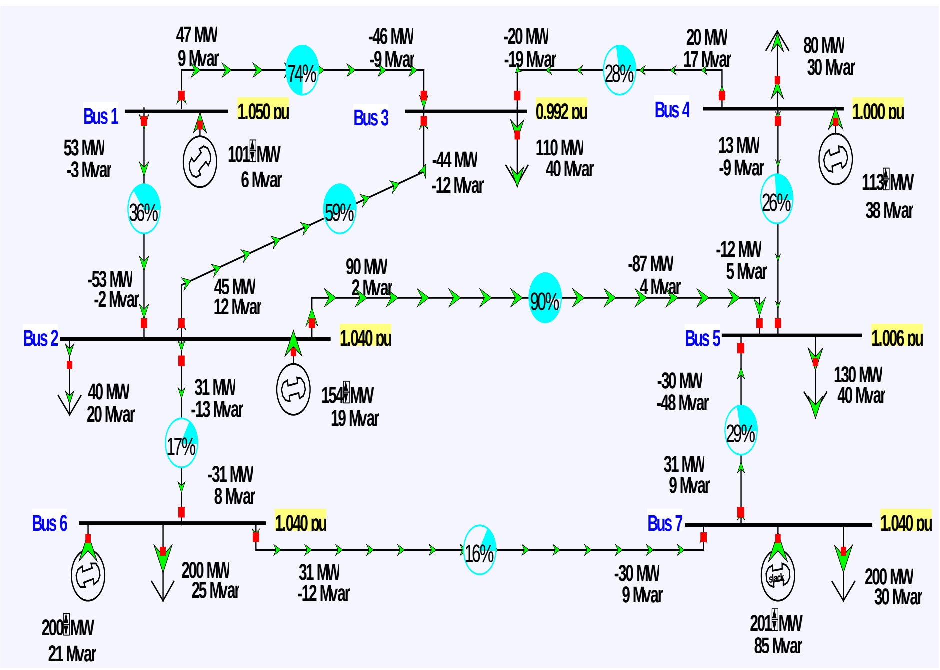
$$\frac{2H_i}{\omega_s}\frac{d\omega_i}{dt} = \frac{2H_i}{\omega_s}\frac{d\Delta\omega_i}{dt} = T_{Mi} - T_{Ei} - D_i\left(\Delta\omega_i\right)$$

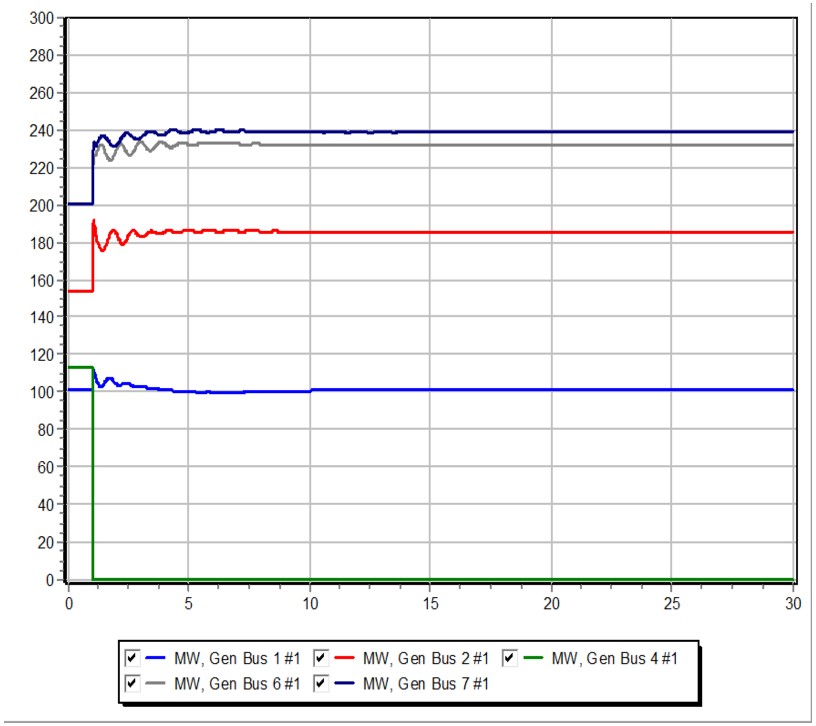
The swing equation is sometimes written with power rather than torque

H_i is the inertia constant, with units of seconds

Seven Bus Example

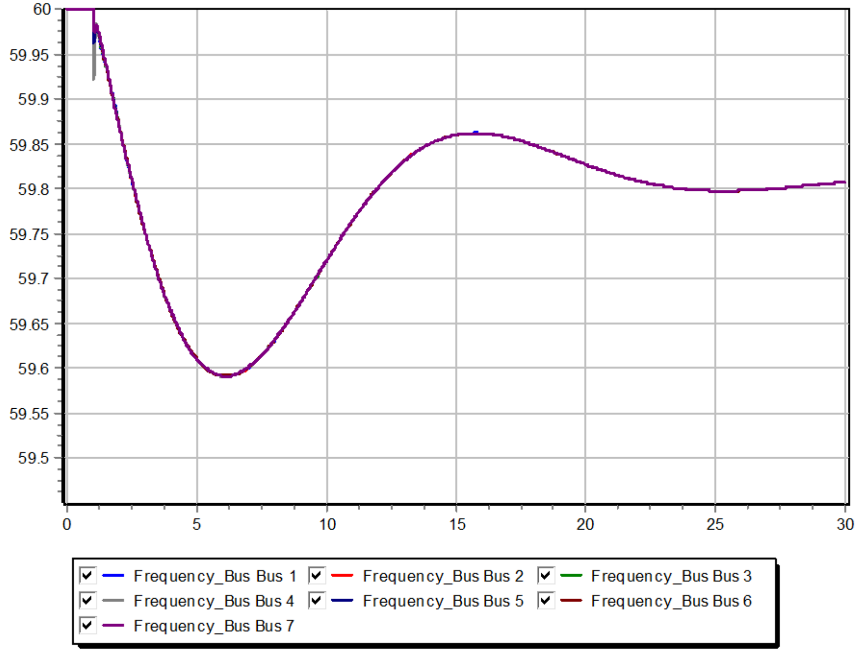
- Example shows response of seven bus, five generator system to losing generator 4

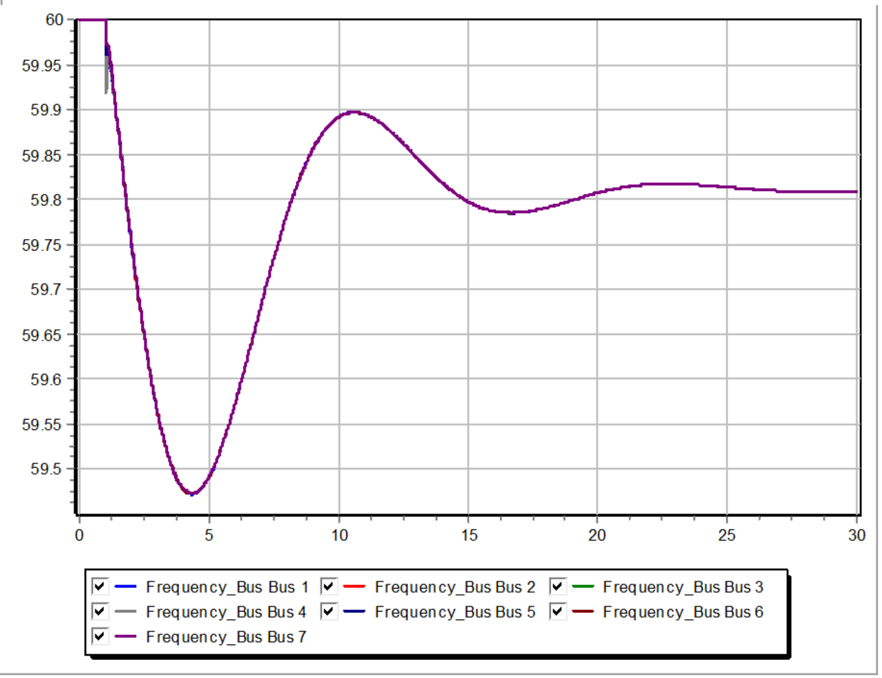




Seven Bus Example, Regular vs. Low Inertia

- Graphs show frequency response for original inertia and ½ original inertia





Frequency Decline in September 2011 Blackout

Figure 14: Actual and Simulated Frequency at Miguel 500 kV Bus

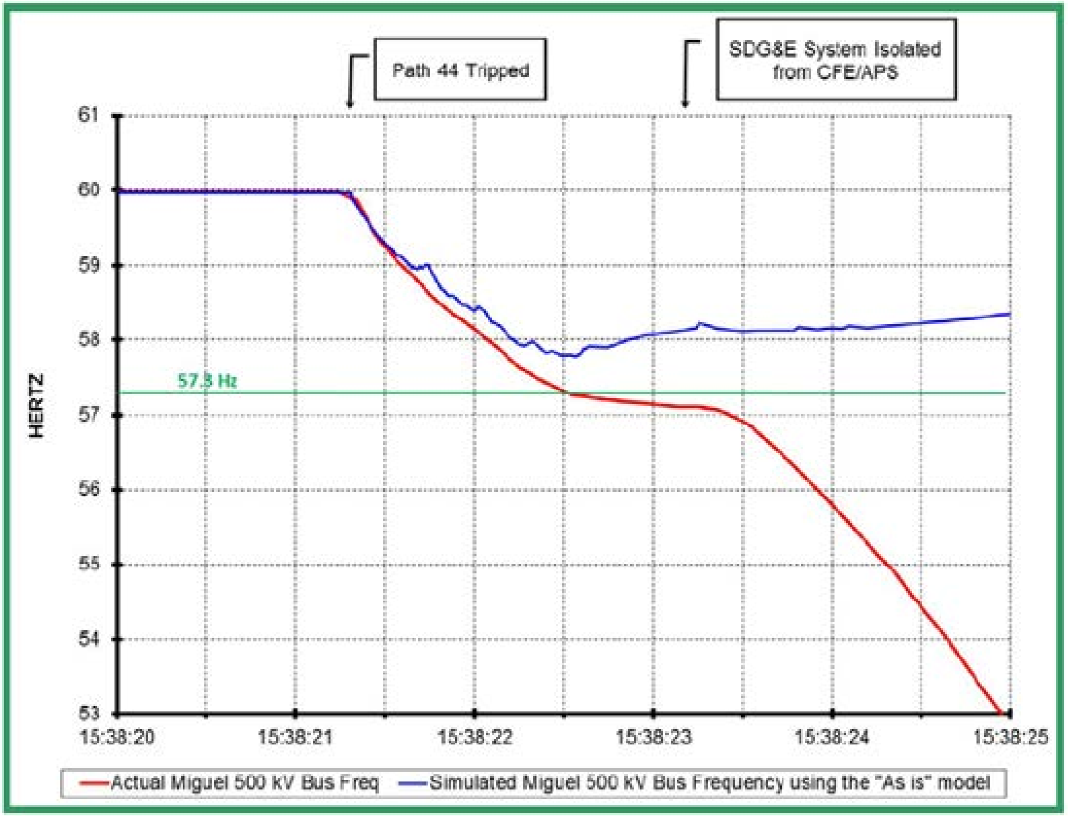


Image Source: *Arizona-Southern California Outages on September 8, 2011 Report*, FERC and NERC,April 2012

Research Objectives

- Power systems with less inertia are less capable of resisting system frequency deviation
  - No effective market mechanism providing financial incentives for market participants to offer inertia services.
  - To construct an effective evaluation approach to assess economic value of the additional inertia services for power systems
- To design a control scheme for fast-acting storage devices to provide inertia services by mimicking inertial response during system dynamics

Initial Research Direction

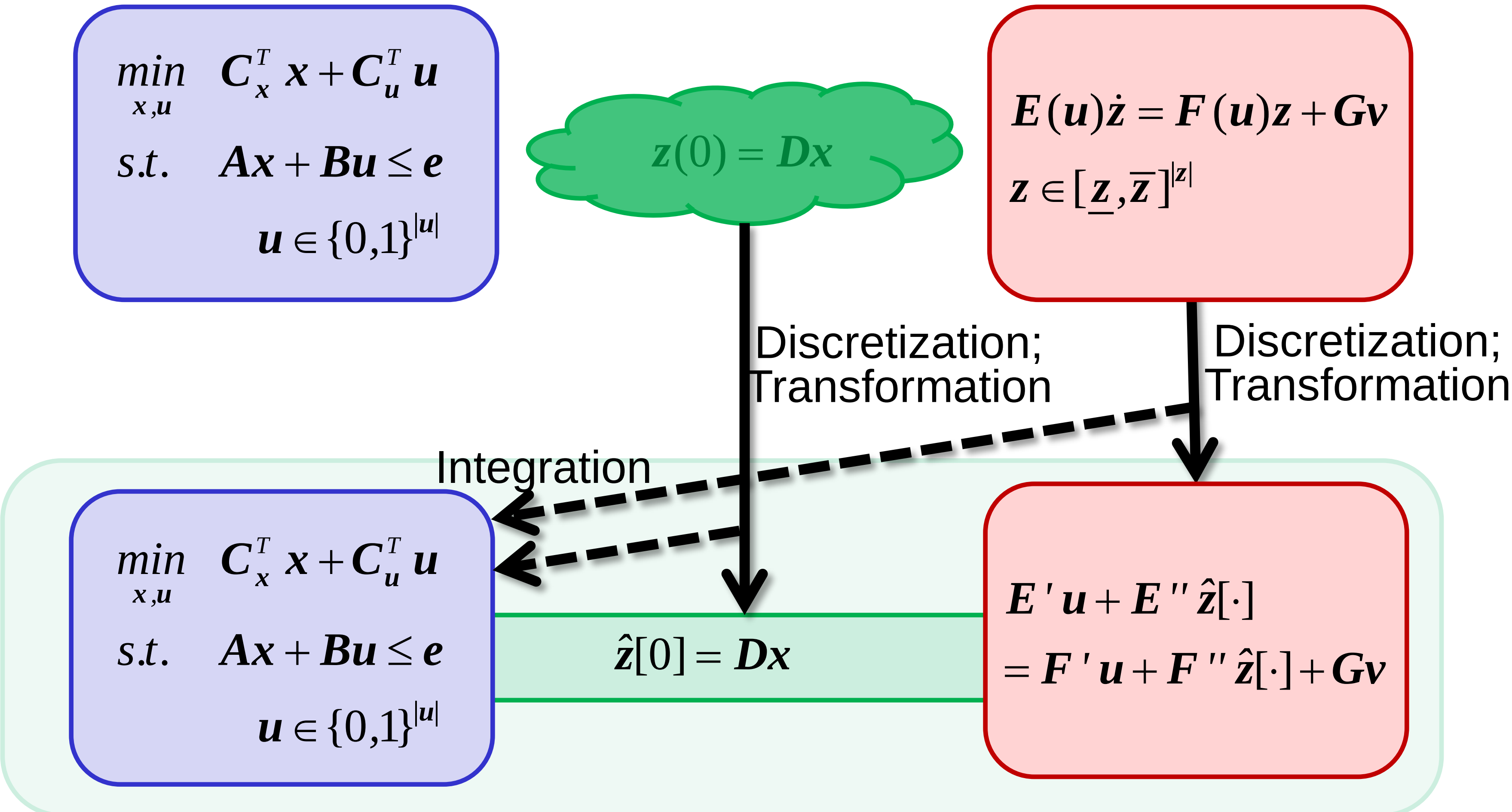
- Embedding dynamic simulation into a unit commitment algorithm
  - Discretizing the dynamic simulation model;
  - Integrating discrete-time dynamic simulation model into steady-state unit commitment model as transient-stability security constraints;
  - Transforming nonlinear constraints into equivalent linear

$$\min_{\mathbf{x},\mathbf{u}} \quad \mathbf{C}_x^T \mathbf{x} + \mathbf{C}_u^T \mathbf{u}$$
$$s.t. \quad \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \le \mathbf{e}$$
$$\mathbf{u} \in \{0,1\}^{|\mathbf{u}|}$$

$$\hat{\mathbf{z}}[0] = \mathbf{D}\mathbf{x}$$

$$\mathbf{E}'\mathbf{u} + \mathbf{E}''\hat{\mathbf{z}}[\cdot] = \mathbf{F}'\mathbf{u} + \mathbf{F}''\hat{\mathbf{z}}[\cdot] + \mathbf{G}\mathbf{v}$$

Simulation Framework



Simulation Framework

$$\min_{\boldsymbol{x},\boldsymbol{u}} \quad \boldsymbol{C}_x^T \boldsymbol{x} + \boldsymbol{C}_u^T \boldsymbol{u}$$
$$s.t. \quad \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u} \le \boldsymbol{e}$$
$$\boldsymbol{u} \in \{0,1\}^{|\boldsymbol{u}|}$$

$\boldsymbol{x}$ and $\boldsymbol{u}$ represent the continuous (e.g., generator output) and discrete (e.g., generator state) variables, respectively, with the corresponding cost coefficients $\boldsymbol{C}_x$ and $\boldsymbol{C}_u$. Constants $\boldsymbol{A}$, $\boldsymbol{B}$ and $\boldsymbol{e}$ are the parameters in the linear constraints.

$$\boldsymbol{z}(0) = \boldsymbol{D}\boldsymbol{x}$$

Values of the steady-state variables $\boldsymbol{x}$ determine the initial values $\boldsymbol{z}(0)$ for dynamic variables $\boldsymbol{z}$.

Simulation Framework

$$\boldsymbol{E}(\boldsymbol{u})\dot{\boldsymbol{z}} = \boldsymbol{F}(\boldsymbol{u})\boldsymbol{z} + \boldsymbol{G}\boldsymbol{v}$$

$$\boldsymbol{z} \in [\underline{\boldsymbol{z}}, \overline{\boldsymbol{z}}]^{|\boldsymbol{z}|}$$

In the transient stability model, $\boldsymbol{z}$ denotes as the generator dynamic variables and $\boldsymbol{v}$ refers to some constants, such as voltage references. $\boldsymbol{E}(\boldsymbol{u})$, $\boldsymbol{F}(\boldsymbol{u})$ and $\boldsymbol{e}$ are the parameters used in the dynamic model. And $\boldsymbol{E}(\boldsymbol{u})$ and $\boldsymbol{F}(\boldsymbol{u})$ depend on the values of $\boldsymbol{u}$.

$$\hat{\boldsymbol{z}}[0] = \boldsymbol{D}\boldsymbol{x}$$

$$\boldsymbol{E}'\boldsymbol{u} + \boldsymbol{E}''\hat{\boldsymbol{z}}[\cdot] = \boldsymbol{F}'\boldsymbol{u} + \boldsymbol{F}''\hat{\boldsymbol{z}}[\cdot] + \boldsymbol{G}\boldsymbol{v}$$

$\hat{\boldsymbol{z}}$ is the discretized representation of variables $\boldsymbol{z}$;
$\boldsymbol{E}'$ and $\boldsymbol{E}''$ are the discretized representation of $\boldsymbol{E}(\boldsymbol{u})$;
$\boldsymbol{F}'$ and $\boldsymbol{F}''$ are the discretized representation of $\boldsymbol{F}(\boldsymbol{u})$;

Assumption and Evaluation Process

- We adopt the uniform frequency model,
  - Uniform frequency is assumed across the gird, with the dynamics represented by a single differential equation
  - Ignores the network effects: assumes that all the generators move coherently as a single lumped mass and the system load damping behavior are also lumped together and modeled as a single constant
- To evaluate the marginal value of additional inertia
  - We perform simulations twice on the same systems without any change except for modifying the total inertia value by a certain amount. The total production cost decrement approximates the economic value of the inertia increment

One Possible Way to Provide Additional Inertia Services

- Fast-acting storages are capable to respond up to its maximum charging/discharging rates quickly
  - Without a control scheme, the storage output is fixed at its scheduled constant value during the system dynamic processes;
  - The core idea in the proposed algorithm is to control the storage output such that the system frequency response behaves as if there is additional inertia, H', into the grid with the storage output fixed at the scheduled value.
- Communication delay and storage device response times are ignored

Illustration of Storage Control Strategy to Mimic Inertia

mechanical input power to unit i

the electrical output to the load, equal to the system load

$$\frac{d\omega}{dt} = \frac{\sum_{i=1}^{I} p_i^{c,m} - p^d - D\Delta\omega + p^s}{\sum_{i=1}^{I} 2H_i}$$

time-varying storage output determined by the proposed control strategy

fixed storage output without any control algorithm

$$\frac{d\omega}{dt} = \frac{\sum_{i=1}^{I} p_i^{c,m} - p^d - D\Delta\omega + p^{s0}}{\sum_{i=1}^{I} 2H_i + 2H'}$$

the "virtual" inertia provided by the storage device

unit i inertia

$$p^s = p^{s0} + 2H'\frac{d\omega}{dt}$$

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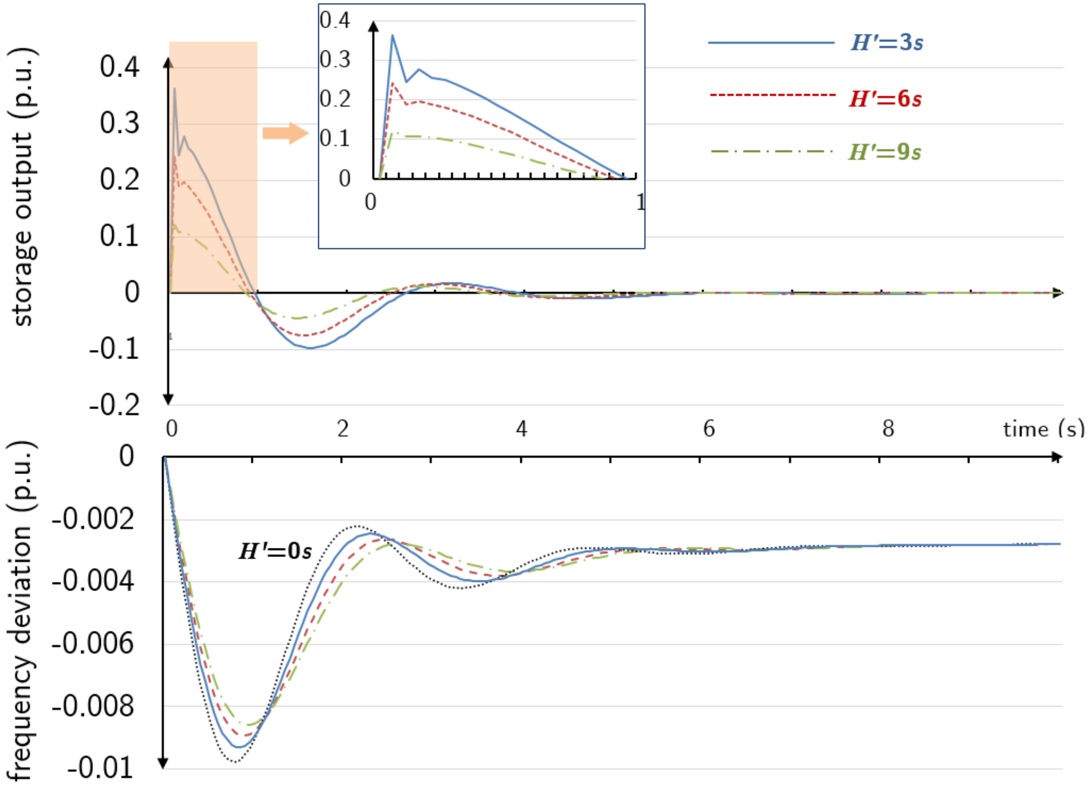
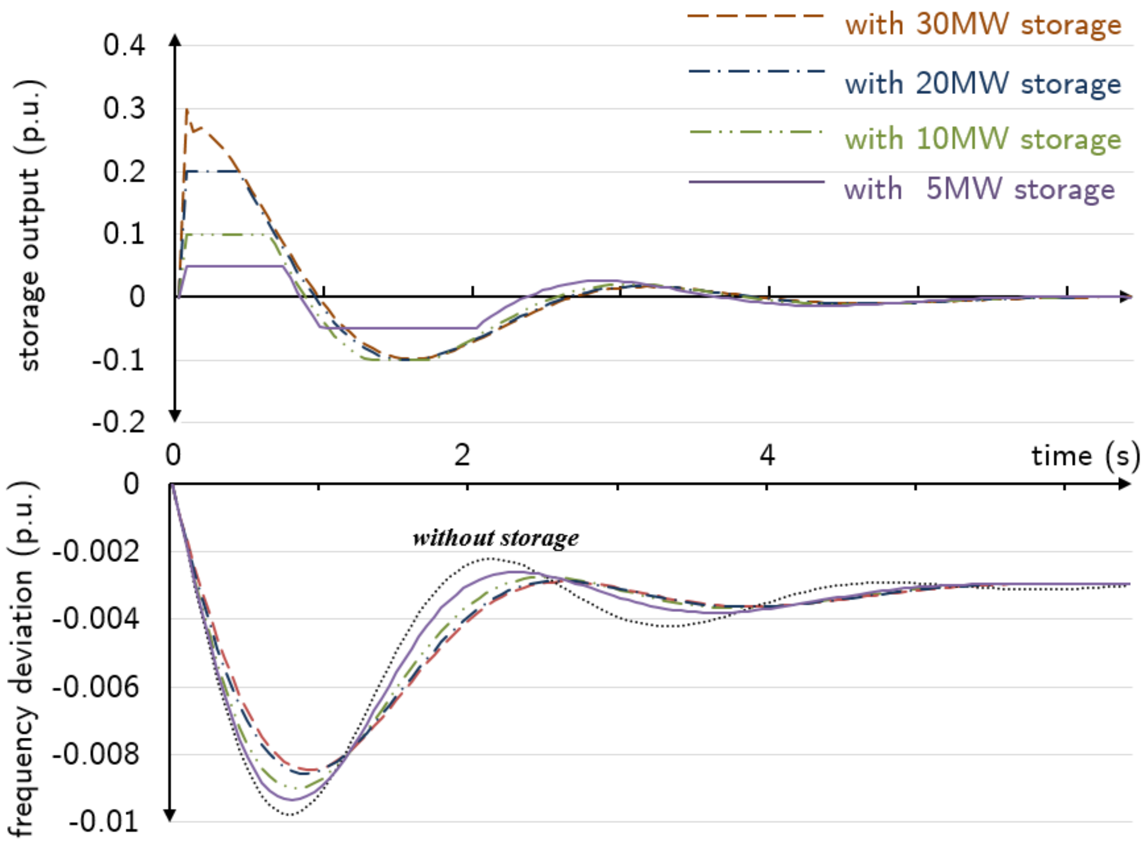
Storage to Mimic Inertia – Numerical Example

- Consider a case with ten 120-MW (=1.2 p.u.) conventional units, used to supply the electricity demand of 10 p.u., and the under-frequency contingency with a sudden load increase of 1 p.u.



Storage to Mimic Inertia – Numerical Example

- For more realistic simulations, we perform simulations setting *H'* = 9 with considering the charging and discharging rate limits.



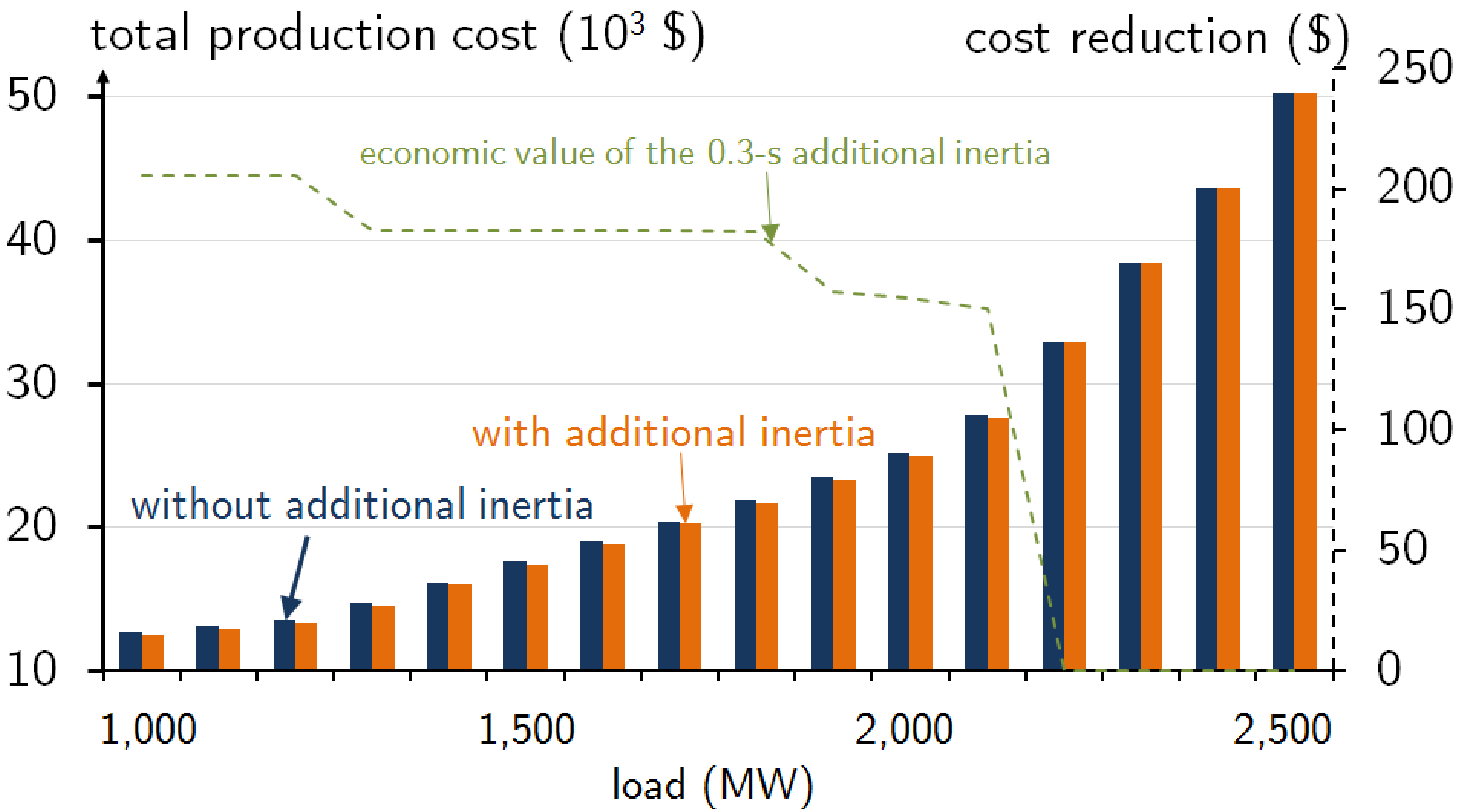
IEEE 24-bus Test System

- We performed extensive studies on a modified version of the 24-bus IEEE reliability test system
  - Obtained the load data by scaling the 2004 WECC load data to the same load shape with an annual peak load of 2,850 MW
  - The up/down/non-spinning reserve requirements are set at 5%, 2% and 5%, respectively;
  - Used a wind turbine model and used historical wind speed data to build the wind power output portfolio

IEEE 24-bus Test System

- We consider a storage device with sufficiently large capability and charging/discharging capacity.
  - And we only utilize the storage to provide additional inertia services for frequency regulation.
- In the first case, we study the economic value of the additional inertia service with respect to the varying load level.
- We devote the second case study to investigate the impacts of wind resource integration on the economic value of power system inertia.

Study I - Varying Load Level



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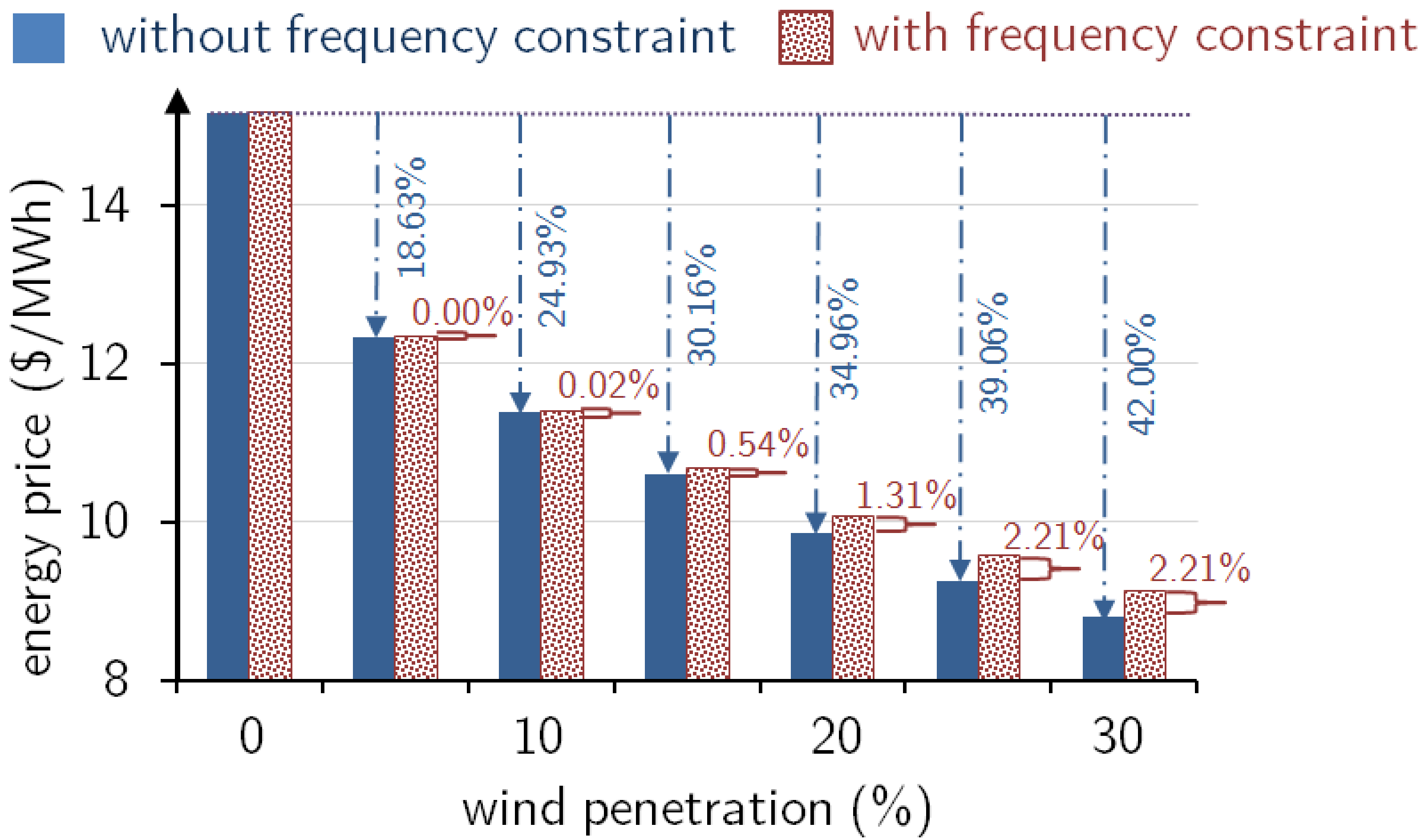
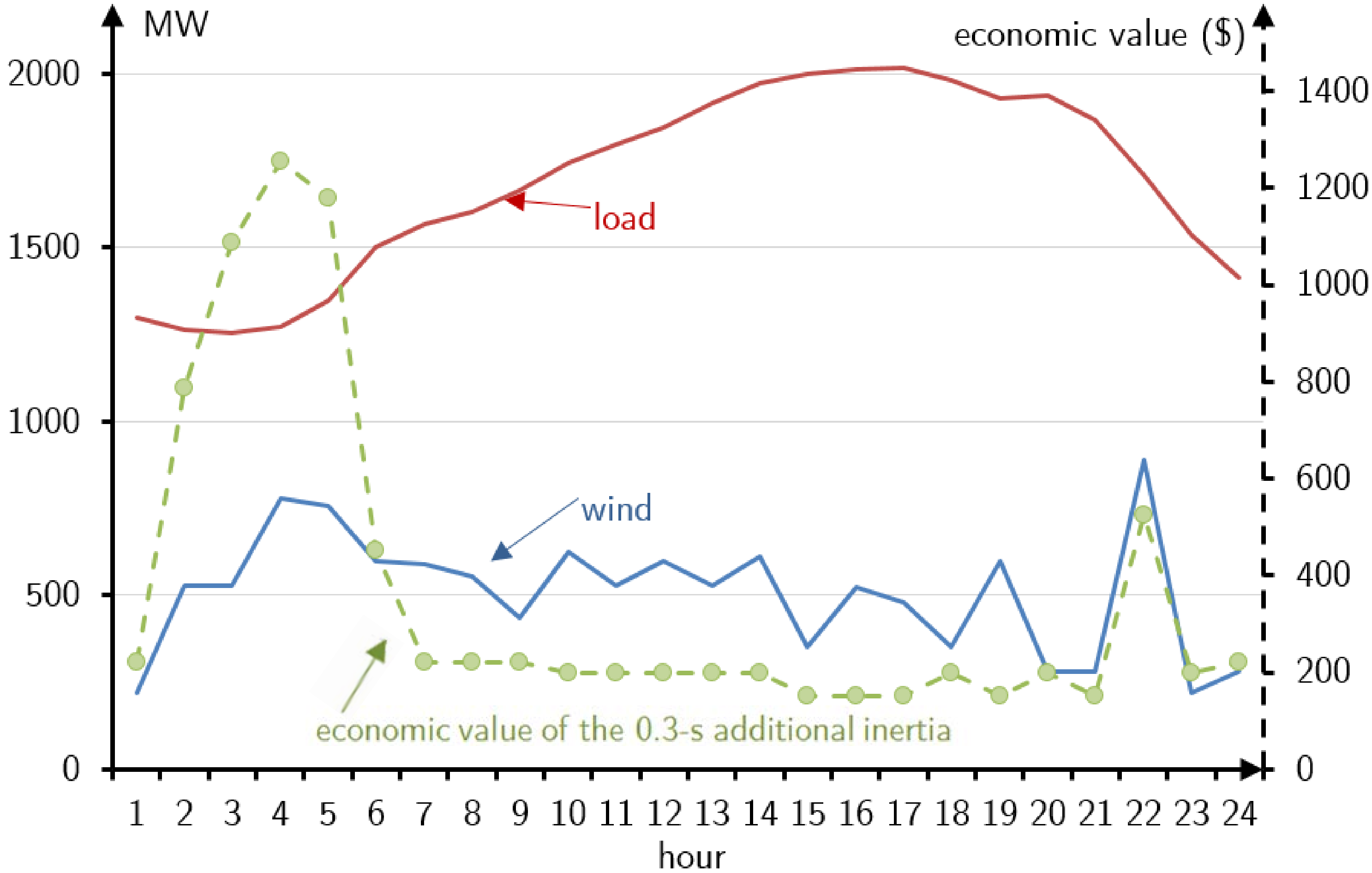
Study I - Varying Load Level

- 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

Case Study II – Impacts of Wind Power



Case Study II - Impacts of Wind Power



Case Study II - Impacts of Wind Power

- As wind generation increases
  - Energy price declines but its contribution gets less significant as it replaces conventional units in consideration of frequency constraint;
  - Total system inertia decreases, resulting in unit re-dispatch to assure sufficient system inertia.
  - More acute for system to request additional inertia service during low net-load hours, such as early morning when load has not climbed up with wind energy of a high value.

Publications

- T. Xu, W. Jang, T. J. Overbye, “An Economic Evaluation Tool on Inertia Services for Systems with Integrated Wind Power and Fast-acting Storage Resources,” HICSS 2016, submitted.
- W. Jang, T. Xu, T. J. Overbye, “Enhancement of System Inertial Frequency Response with Fast-acting Storage Devices,” PSCC 2016, abstract accepted.

Future Work

- To construct a comprehensive market simulation tool with integration of dynamic performance security constraints
  – When more complete dynamics are added consider the degree to which the present approach can be expanded versus needing to be replaced
  – Full dynamic model will be used to verify whether the obtained unit commitment plan guarantees the post-contingency frequency deviation within the required bounds.