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Frequency Response Assessment and Improvement of Three Major North American Interconnections due to High Penetrations of Photovoltaic Generation

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Overview

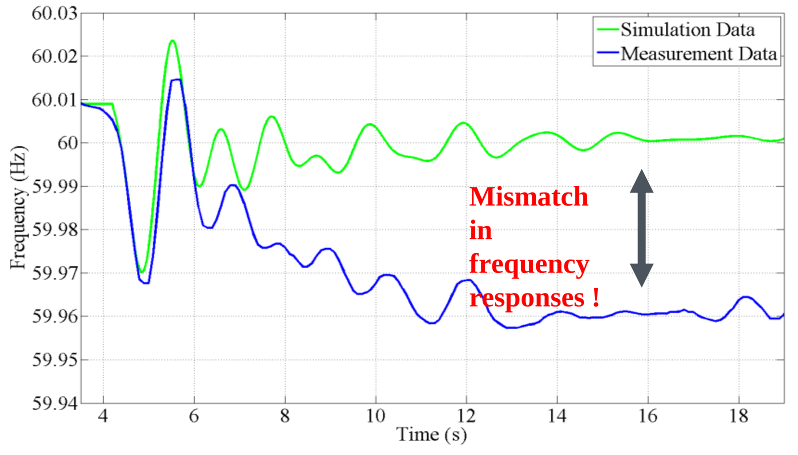
- High PV penetration scenarios for U.S. interconnection grids
- Impact of high PV at both the interconnection and balancing authority levels
- Mitigation strategies for low system inertia and reduced frequency response
- Additional studies for high PV interconnection grids

Project Innovation Aspects

- Develop high PV penetration scenarios based on the measurement-validated interconnection models and projected PV distribution
- Simulate the impact of high PV at both the interconnection (>80%) and balancing area levels (>=100%)
- Production-grade solar inverter with inertia control function for frequency response improvement

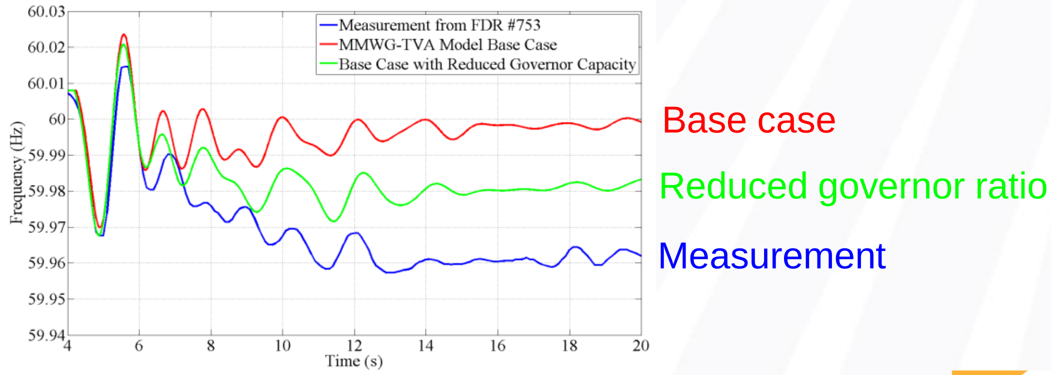
Base Model Validation Using Measurements - Introduction

- Why is the simulated EI primary frequency response significantly higher than measured values?
- Sensitivity study results.
  - **Governor ratio/spinning reserve (major)**
  - **Governor deadband (major)**
  - Governor droop
  - Load composite
  - The outer loop control
  - Inertia
  - Frequency dependent network



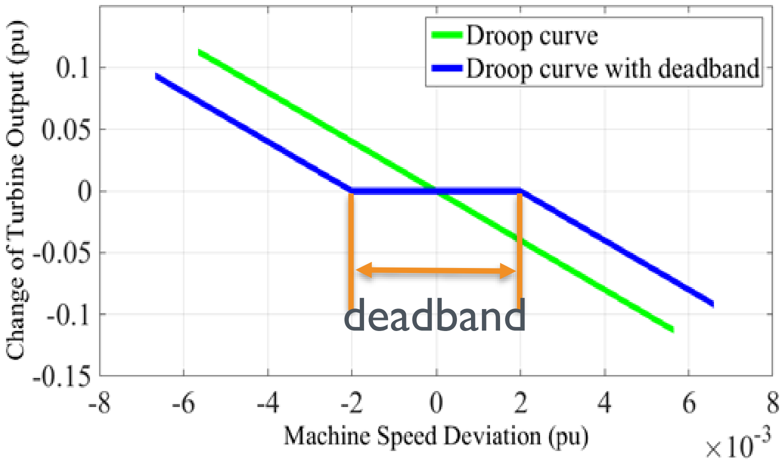
Base Model Validation Using Measurements – Governor Ratio

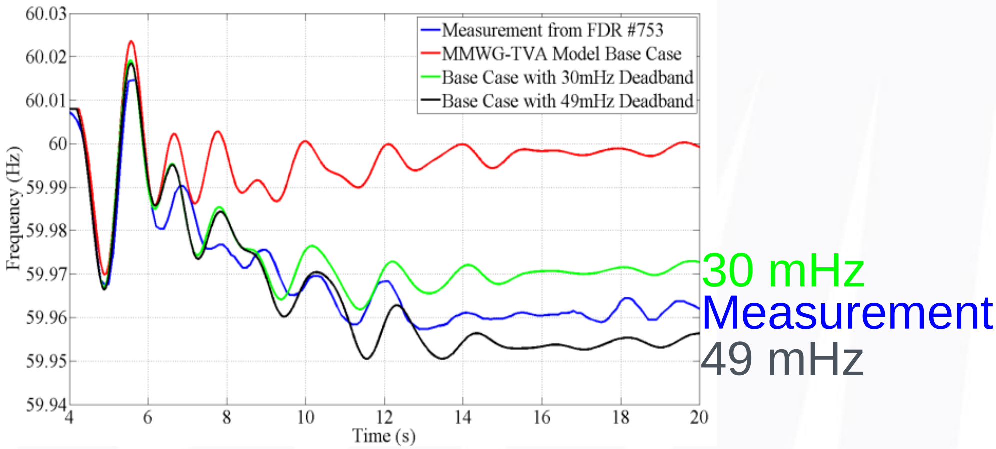
- Governor ratio is the fraction of generation capacity that is providing governor response.
- The ratio is currently around 80% in the EI MMWG models. Based on FNET/GridEye monitoring data, this ratio for EI is likely lower than 30% to match measurement.



Base Model Validation Using Measurements – Governor Deadband

- Governor deadband is adopted to avoid excessive turbine control actions within normal frequency variation range.
- Not typically modeled in EI MMWG model.





Base Model Validation Using Measurements – Results

Measurement locations at EI edges

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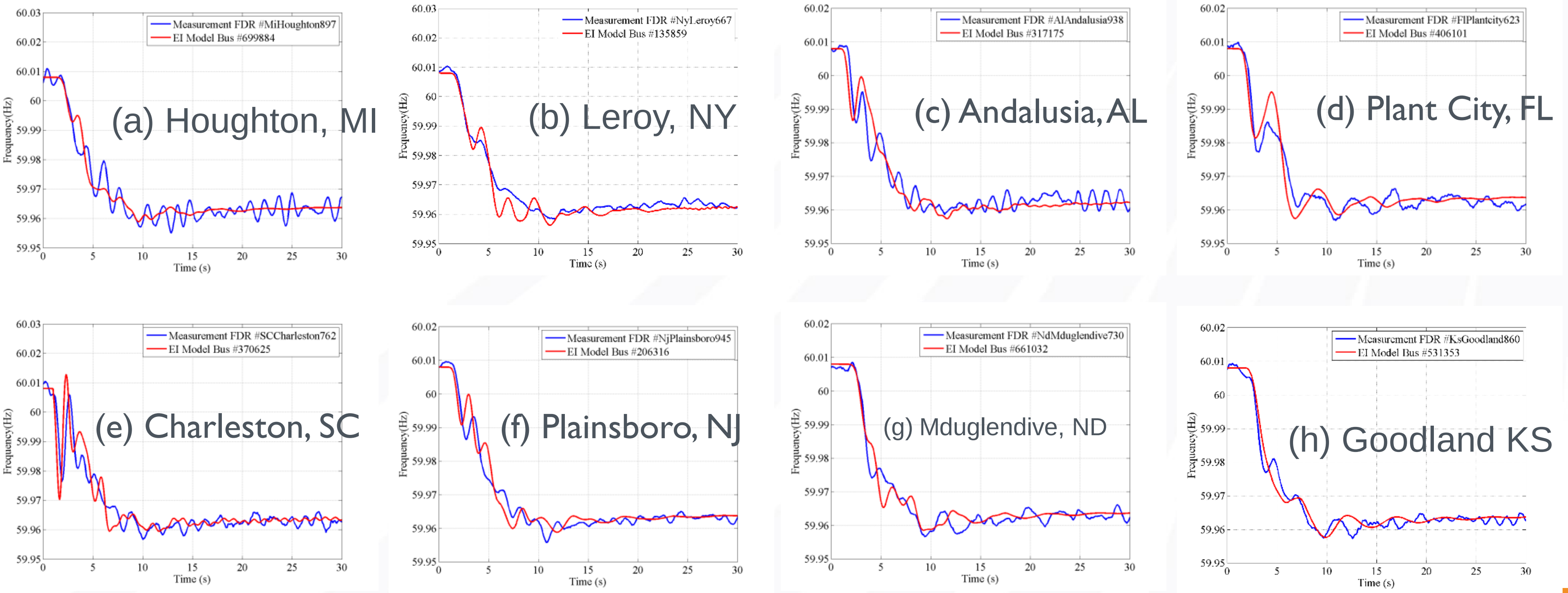
Base Model Validation Using Measurements – Validation Accuracy at Grid Edges

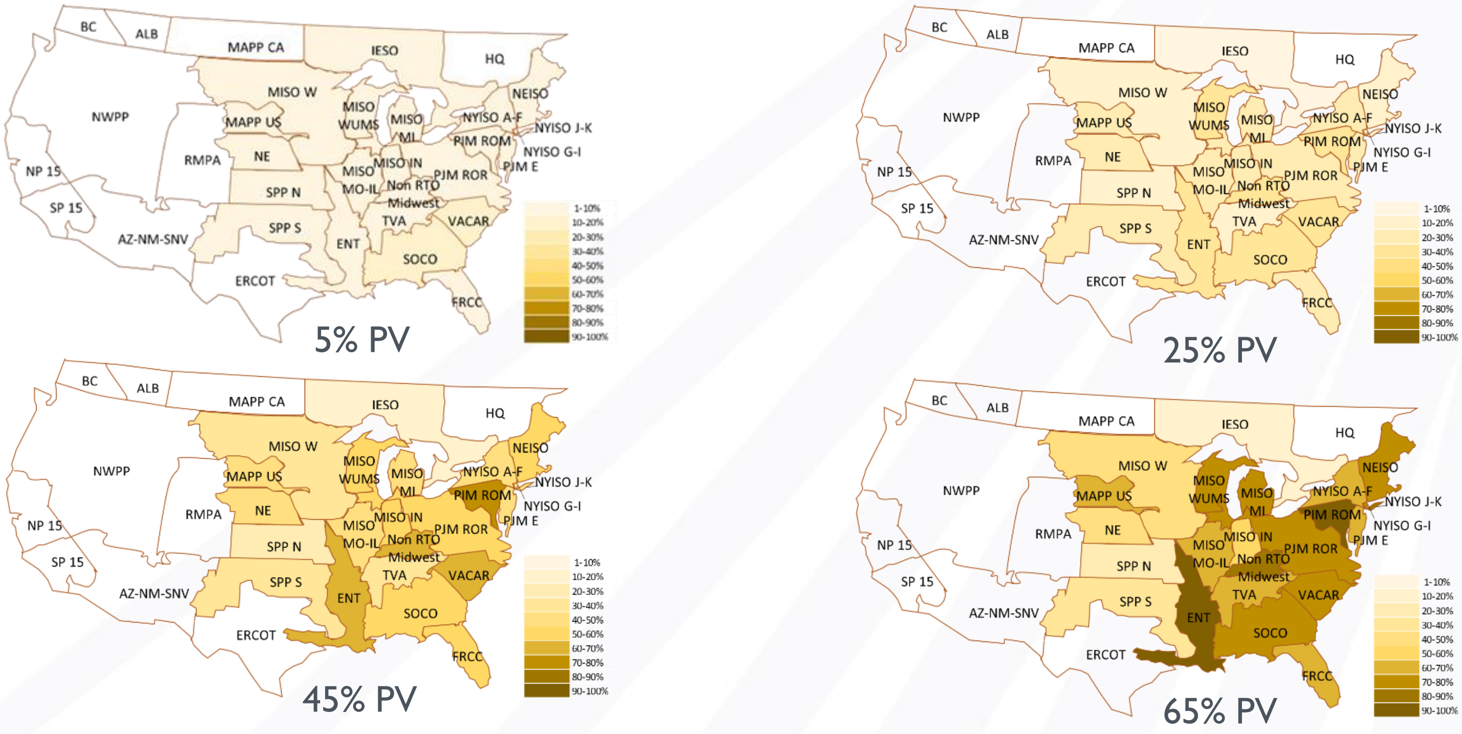


High PV Scenario Generation Mix Determination

- The generation mix of simulation scenario
- 18 cases total (for EI, WECC and ERCOT)

Scenario	Instantaneous PV Penetration Level	Instantaneous Wind Penetration Level	Total Instantaneous Renewable Penetration Level
Interconnection Level Scenario 1	5%	15%	20%
Interconnection Level Scenario 2	25%	15%	40%
Interconnection Level Scenario 3	45%	15%	60%
Interconnection Level Scenario 4	65%	15%	80%
Regional Scenario	100%	0%	100%

PV Instantaneous Penetration Rate Distribution in the EI

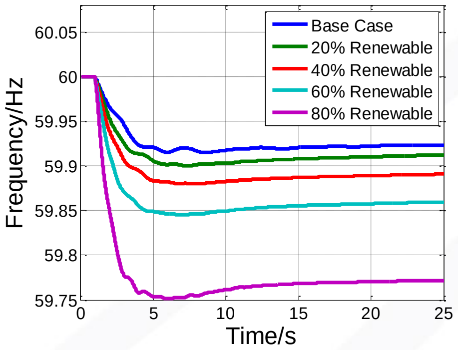


PV geographic distribution in the EI

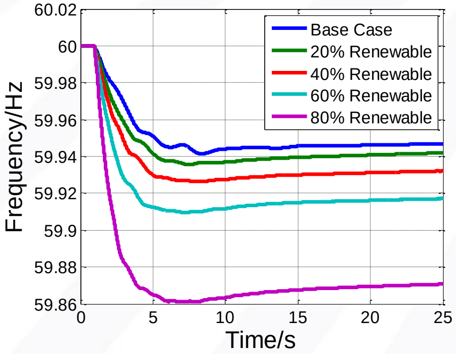
Task 2.1: EI Frequency Response under High PV Penetration

Test resource contingencies in the EI

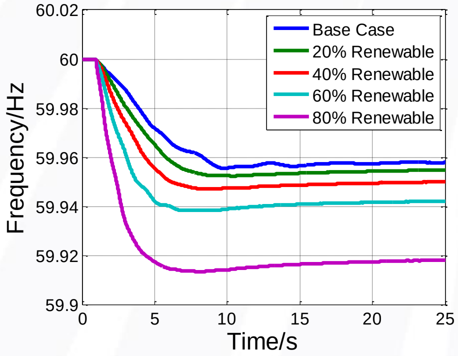
Contingency	Description	Unit Location	Generation loss (MW)
1	The largest resource event in last 10 years	Five units in south Indiana (August 4, 2007 Disturbance)	4,500
2	An N-2 contingency	Two Braidwood Nuclear Units, Illinois	2,250
3	An N-1 contingency	One Browns Ferry Nuclear Unit, Alabama	1,128



Largest Resource Event (4,500 MW loss)



An N-2 Contingency (2,250 MW loss)



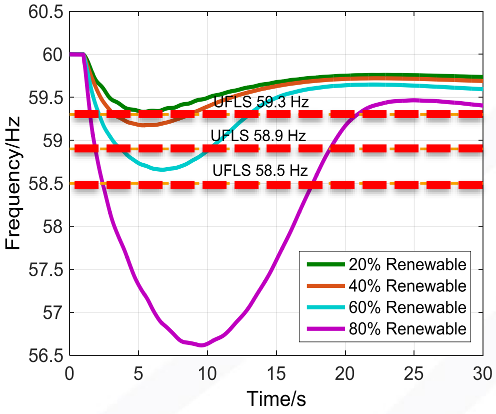
An N-1 Contingency (1,128 MW loss)

The EI frequency responses in different high PV scenarios

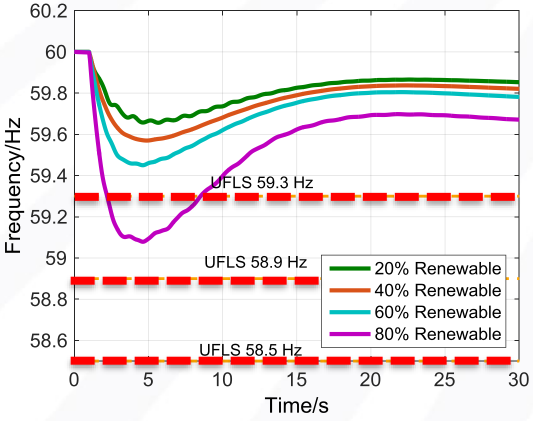
Task 2.1: ERCOT frequency response under high PV penetration

Test resource contingencies in ERCOT

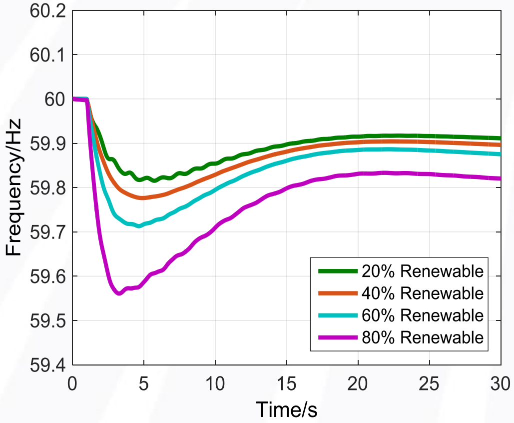
Contingency	Description	Unit Location	Gen. loss (MW)
1	The largest N-2 contingency	Two South Texas Nuclear Units	2,740
2	An N-2 contingency	Two Martin Lake Units	1,370
3	An N-1 contingency	One Martin Lake Unit	685



Contingency 1: 2,740 MW generation loss



Contingency 2: 1,370 MW generation loss



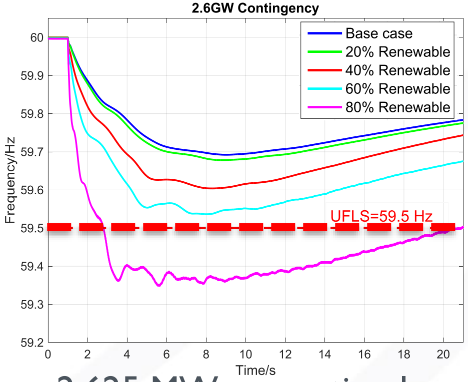
Contingency 3: 685 MW generation loss

The ERCOT frequency responses in different high PV scenarios

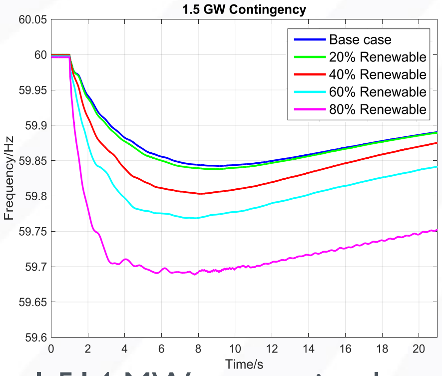
Task 2.1: WECC frequency response under high PV penetration

Test Contingencies in the WECC

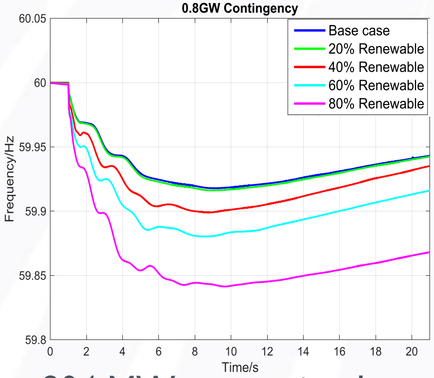
Contingency #	Description	Unit Location	Gen. loss (MW)
1	The largest N-2 contingency	Loss of the two largest generating units in the Palo Verde nuclear facility.	2,625
2	An N-2 contingency	Loss of the two units in the Colstrip coal power plant	1,514
3	An N-1 contingency	Loss of one unit in the Comanche generating station	804



2,625 MW generation loss



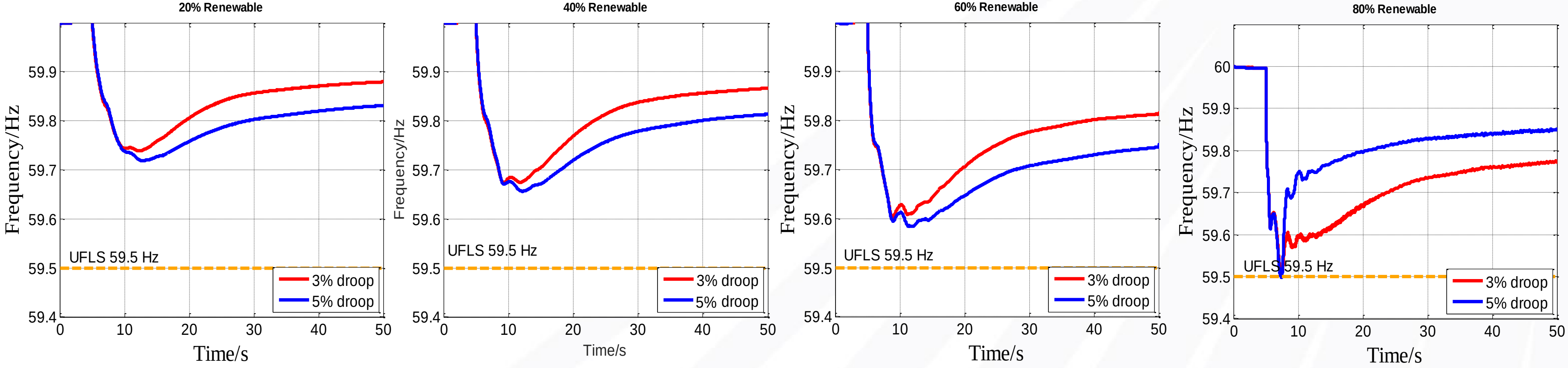
1,514 MW generation loss



804 MW generation loss

The WECC frequency responses in different high PV scenarios

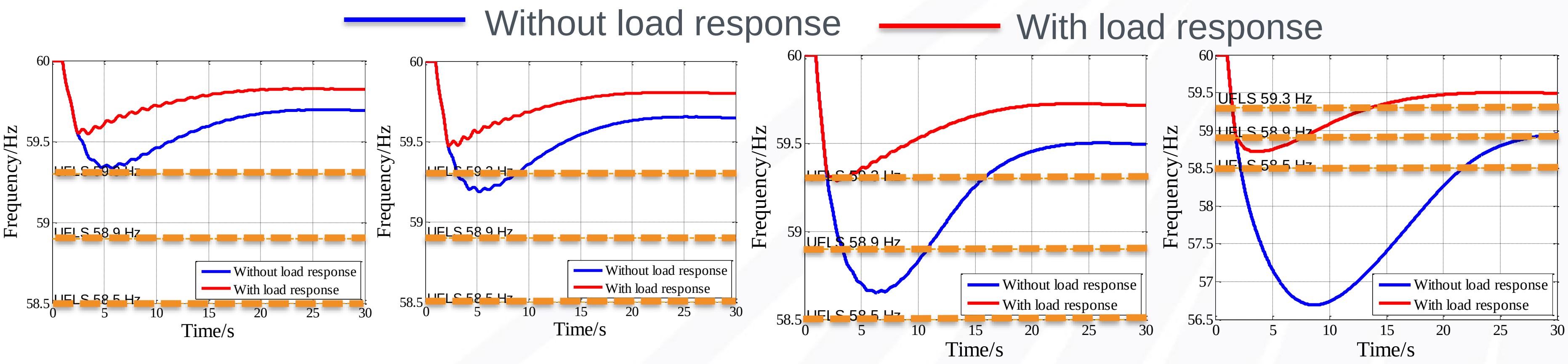
Subtask: Using existing resources to improve frequency response in WECC – changing governor droop



(a)20% renewable **(b) 40% renewable** **(c) 60% renewable** **(d) 80% renewable**

- A 3% governor droop can significantly improve the WECC frequency nadir and settling frequency.
- Because of the faster governor response to the generation loss contingency.

Using existing resources to improve frequency response in ERCOT– FFR provided by load



(a)20% renewable (b) 40% renewable (c) 60% renewable (d) 80% renewable

ERCOT frequency responses with fast load response (2.75 GW generation loss, UFLS disabled)

- Frequency nadir and settling frequency increased significantly with FFR.
- FFR provided by load response is highly efficient in supporting frequency response when the governor response of synchronous generators is insufficient.

Implement the proposed artificial inertia/governor/AGC schemes on GE's utility-level PV inverter

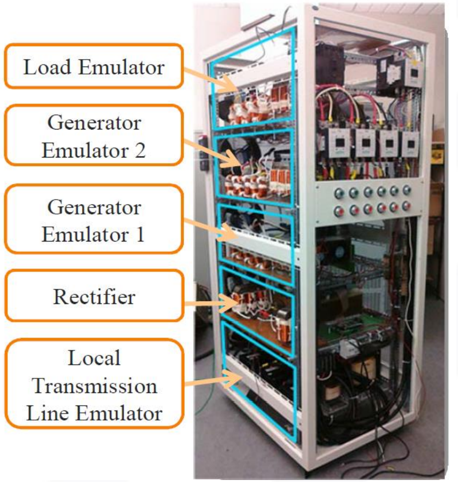
- Solar inertia evaluation system:
  - The inverter controller: MarkVIe based actual inverter control
  - The inverter and the grid: RTDS

GE Brilliance Solar Inverter HIL system

Test the PV inverter with artificial inertia/governor/AGC functions in CURENT Hardware Testbed.

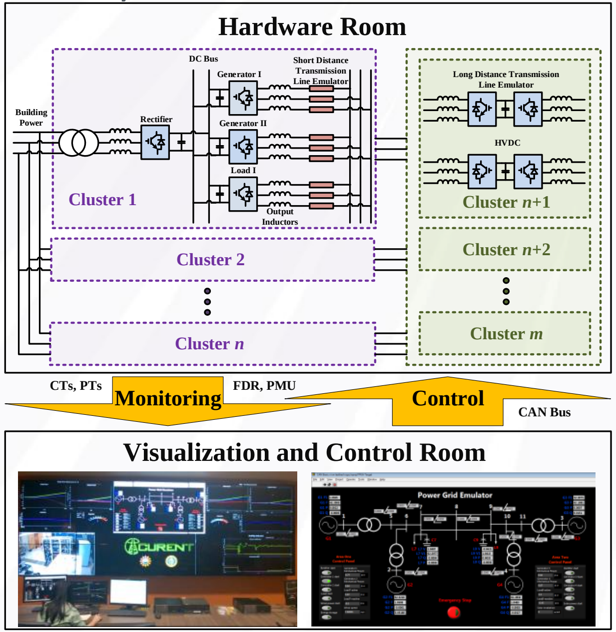
- CURENT HTB Introduction
  - CURENT HTB consists of modular and reprogrammable three-phase converters and a reconfigurable structure to emulate large scale power systems.

HTB Hardware room



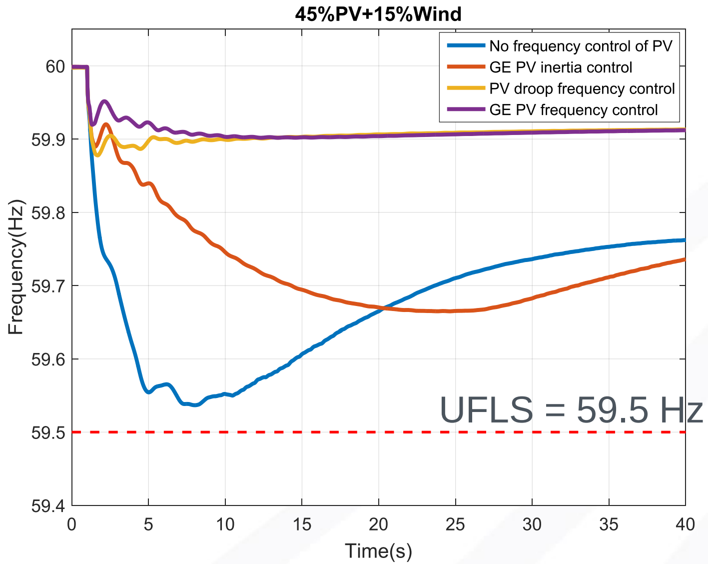
Configuration of one HTB cabinet

CURENT Hardware Testbed

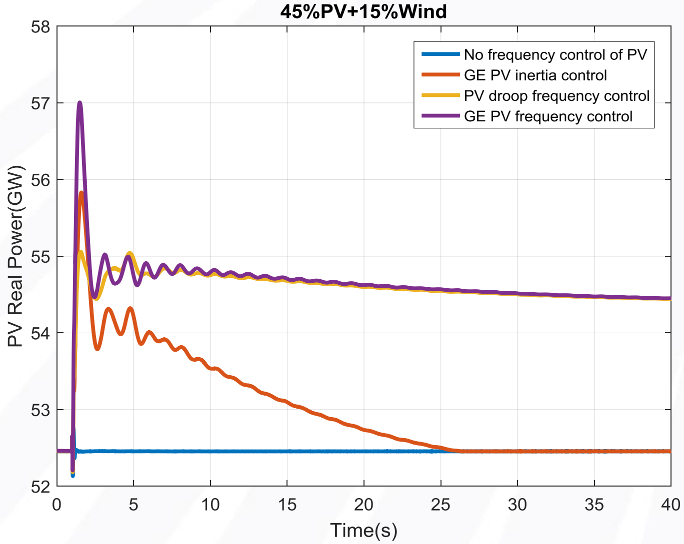


Architecture of the CURENT Hardware Testbed

PV inverter frequency control in the WECC high PV models



Frequency



PV real power

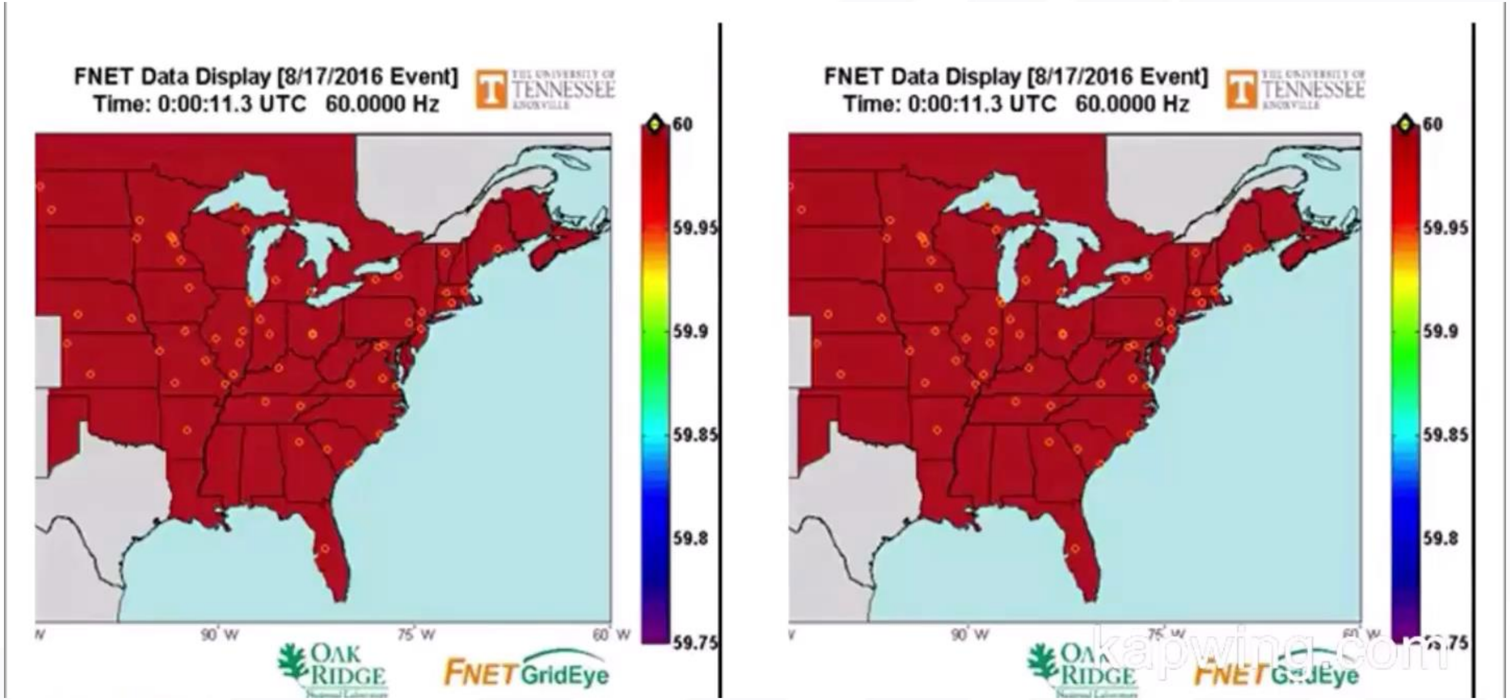
WECC frequency response and PV real power with inverter frequency control (45% PV + 15% WT)

Summary of additional studies

- Impact of high PV penetration on electromechanical wave propagation
- Impact of high PV penetration on FRCC-EI out-of-step stability
- Impact of high PV penetration on EI inter-area oscillations
- Inter-area oscillation damping using PV
- Impact of high PV penetration on transient stability
- Impact of high PV penetration on ERCOT voltage stability
- PV synthetic inertia location sensitivity study on the WECC system

Additional Studies: Impact of High PV Penetration on Electromechanical Wave Propagation

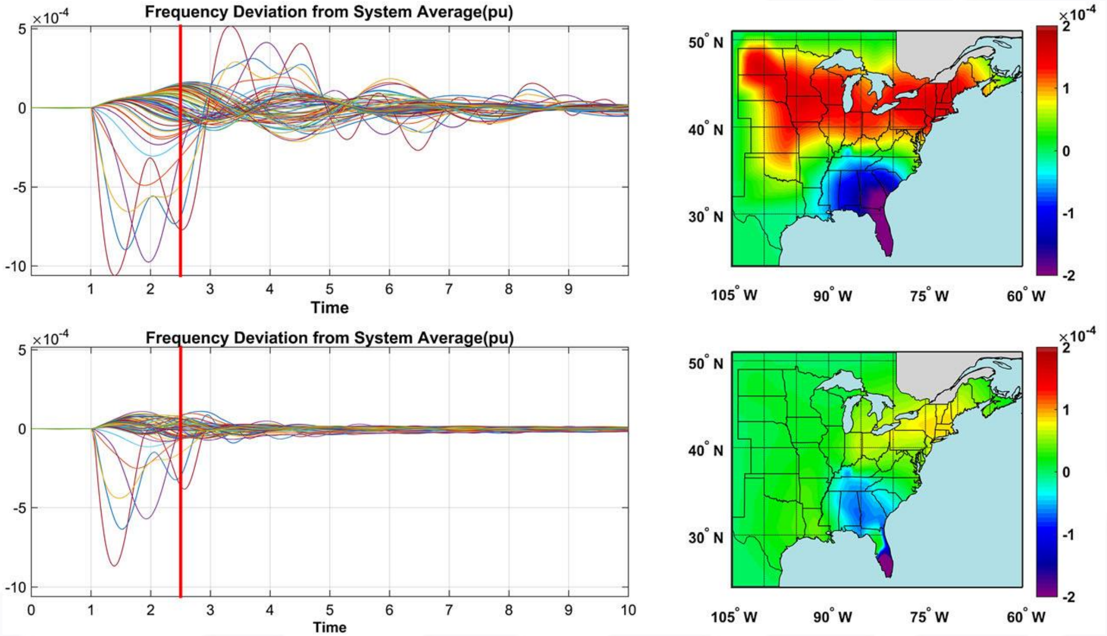
- Comparison of wave propagation between BAU and high PV (video link)



Preliminary results on oscillation damping using solar

No control

Oscillation damping using solar



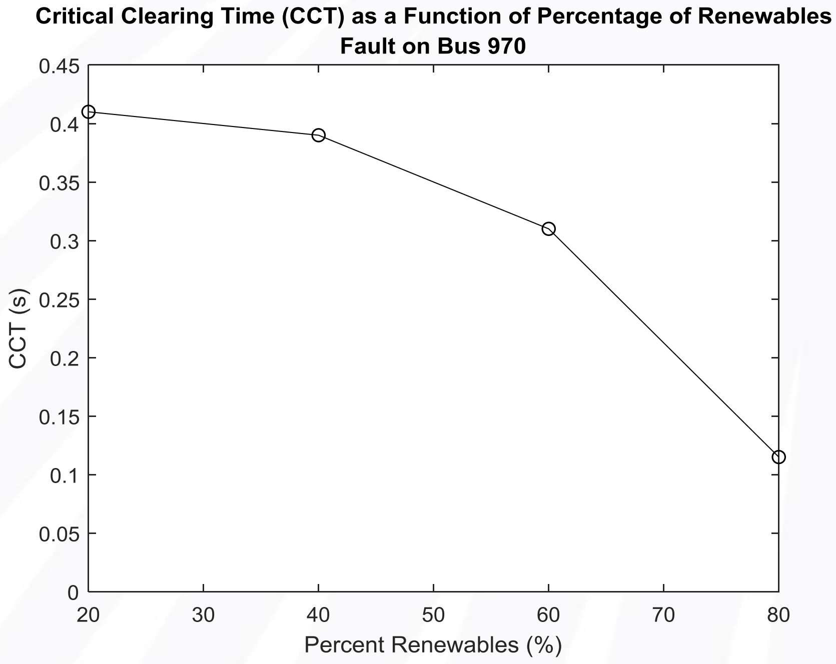
EI system inter-area oscillation damping using wide-area solar PV PSS control.

[1]. Liu, Y., Zhu, L., Zhan, L., Gracia, J.R., King, T.J. and Liu, Y., 2016. Active power control of solar PV generation for large interconnection frequency regulation and oscillation damping. International Journal of Energy Research, 40(3), pp.353-361.

[2]. Liu, Y., You, S. and Liu, Y., 2017. Study of wind and PV frequency control in US power grids—EI and TI case studies. IEEE Power and Energy Technology Systems Journal, 4(3), pp.65-73.

Additional Study: Impact of high PV penetration on transient stability (Lead: ORNL. Participant: UTK)

- Non-linear correlation between CCT and the renewable penetration rate
  - The stability slightly decreases when renewable increases up to 45% PV penetration and 15% wind penetration.
  - By the time the PV penetration reaches 65% with 15% wind, the stability decreases considerably.



CCT vs. renewable penetration

Publications

Journal:

- [J1] S. You, Y. Liu, J. Tan, Y. Liu. Y. Zhang. “Improve Primary Frequency Response Without Curtailing Solar Output in High Photovoltaic Interconnections — Case Studies in the U.S.” *Sustainable Energy, IEEE Transactions on,* 2018. (Published).
- [J2] Y. Liu, S. You, J. Tan, Y. Zhang, Y. Liu, "Frequency Response Assessment and Enhancement of the U.S. Interconnections towards Extra-High Photovoltaic Generation Penetrations — an Industry Perspective," Power Systems*, IEEE Transactions on,* . (Published).
- [J3] Y. Liu, S. You, X. Zhang, S. Hadley, and Y. Liu, "Study of Advanced Renewable Generation Control in the U.S. Power Grid – ERCOT and TI Case Studies," *IEEE Power and Energy Technology Systems Journal,* (Published)
- [J4] S. You, Y. Liu, G. Kou, X. Zhang, S. Hadley, and Y. Liu, "Non-Invasive Identification of Inertia Distribution Change in High Renewable Systems Using Distribution Level PMU," *Power Systems, IEEE Transactions on,* (Published).
- [J5] S. You, G. Kou, Y. Liu, M. J. Till, Y. Cui, and Y. Liu, "The Impact of High Renewable Penetration on the Inter-Area Oscillation of the U.S. Eastern Interconnection (EI)," *IEEE Access,* 2017 (Published)

Conference:

- [C1] S. You, Y. Liu, and Y. Liu, " U.S. Eastern Interconnection (ERCOT) Electromechanical Wave Propagation and the Impact of High PV Penetration on Its Speed,“2018 IEEE PES T&D Conférence & Exposition, 2018.(Published)
- [C2] S. You, Y. Liu, Y. Liu, A. Till, J. Tan, Y. Zhang, and M. Gong. Energy Storage for Frequency Control in High Photovoltaic Power Grids. 2018 North American Power Symposium. (Accepted)
- [C3]J. Tan, Y. Zhang, S. S. Veda, T. Elgindy, and Y. Liu, "Developing High PV Penetration Cases for Frequency Response study of U.S. Western Interconnection," in *The 9th Annual IEEE Green Technologies Conference*, Denver, Colorado, March 2017, pp. 1-5. (Published)
- [C4] J. Tan, Y. Zhang, S. You, Y. Liu, Y. Liu. Frequency Response Study of U.S. Western Interconnection under Extra-High Photovoltaic Generation Penetrations. IEEE PES General Meeting. 2018.(Accepted)
- [C5]S. You, X. Zhang, Y. Liu, Y. Liu, and S. W. Hadley, "Impact of High PV Penetration on U.S. Eastern Interconnection Frequency Response," in *IEEE Power and Energy Society General Meeting,* 2017. (Published)
- [C6] J. Till, S. You, Y. Liu, P. Du. Impact of High PV Penetration on Voltage Stability. MEDPOWR 2018 conference (accepted)

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