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Smart PV Frequency Control based on Real-time System Situational Awareness

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Oak Ridge National Laboratory | The University of Tennessee Knoxville | GE | NREL National Renewable Energy Laboratory

Overview

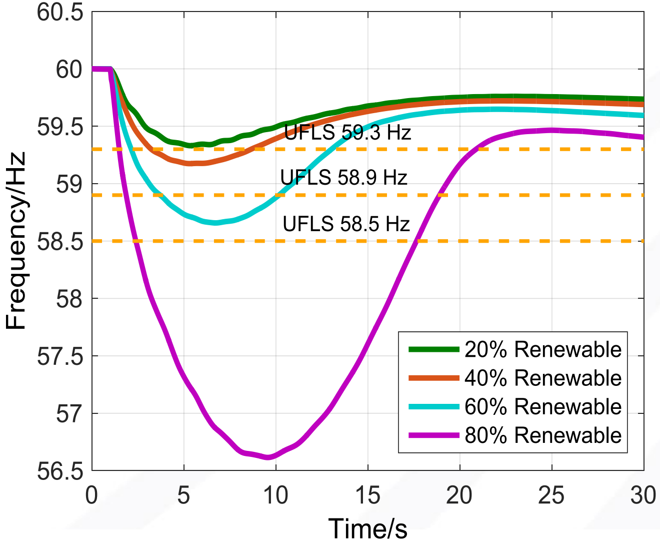
- Develop a system inertia estimation algorithm using ambient synchrophasor measurement.
- Develop a smart PV frequency control approach based on estimated system inertia.
- Test on GE PV inverters and WECC high PV models
- Challenges

Project Objectives

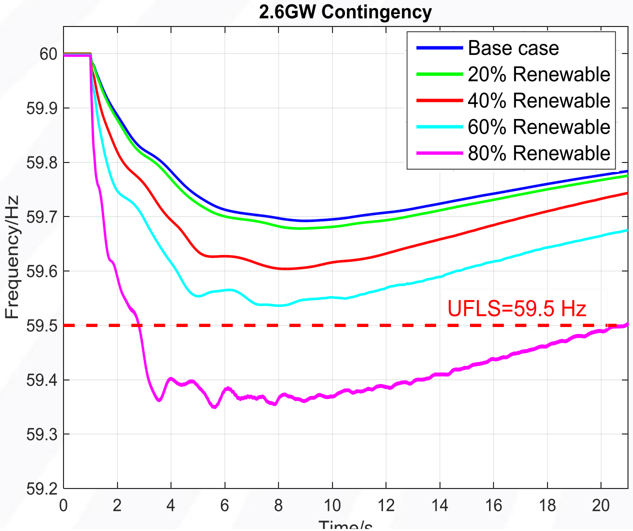
- Innovative features of the project
  - This project aims at developing and demonstrating a smart PV inertia control design for better control effect and lower operation cost.
  - The new technology will be validated using the detailed U.S. high PV interconnection models.
  - The new technology will be demonstrated using the production-grade PV inverter.

Background – System Frequency Response Change in High PV Penetration

- System frequency response decreases with the increase of PV penetration.
  - Inertia decreases
  - Governor response decreases



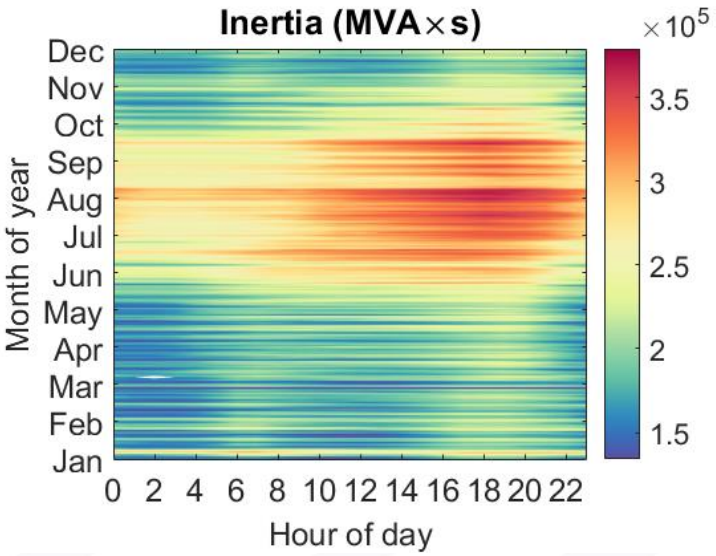
The ERCOT frequency responses in different high PV scenarios (2,750 MW generation loss)



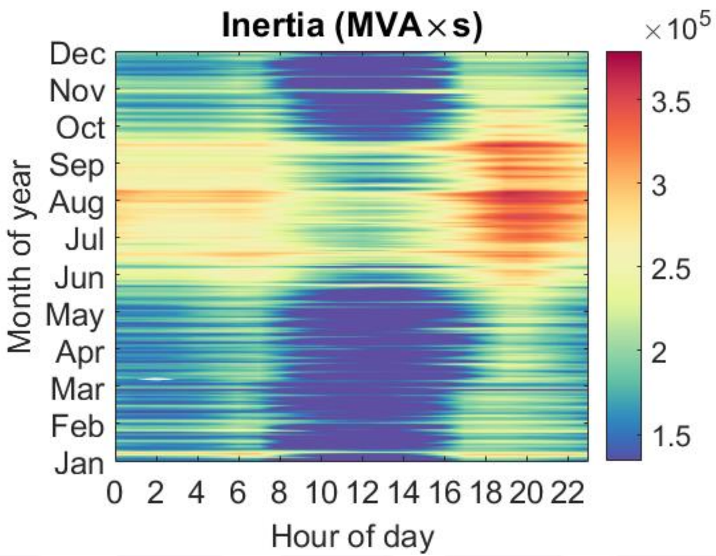
The WECC frequency responses in different high PV scenarios (2,625 MW generation loss)

Background – System Inertia Change in High PV Penetration

- System inertia may fluctuate significantly on an hourly basis.
- Smart frequency control based on real-time system inertia information can maximize energy savings and economic benefits from PV.



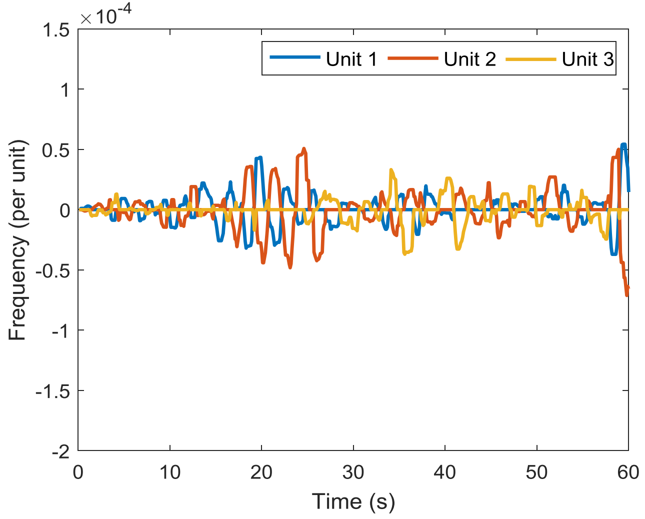
10% PV penetration



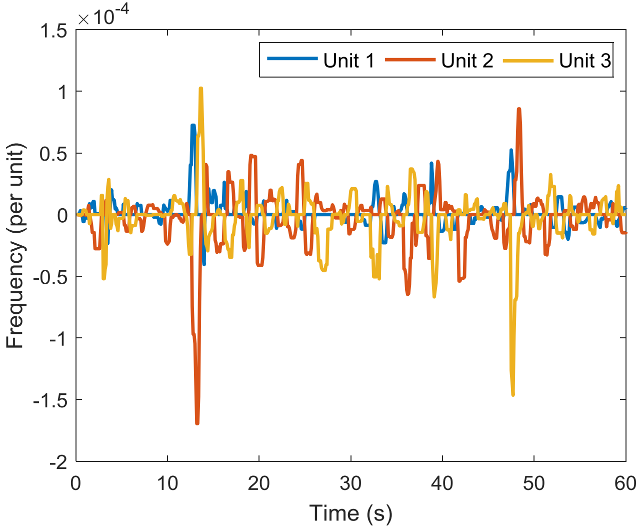
50% PV penetration

Machine-learning-based inertia estimation — extract informative features

- **Inertia and ambient frequency variation**



(a) 100% inertia

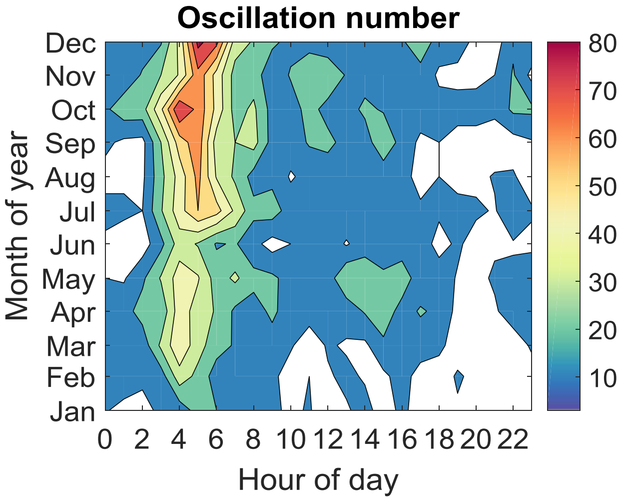


(b) 50% inertia

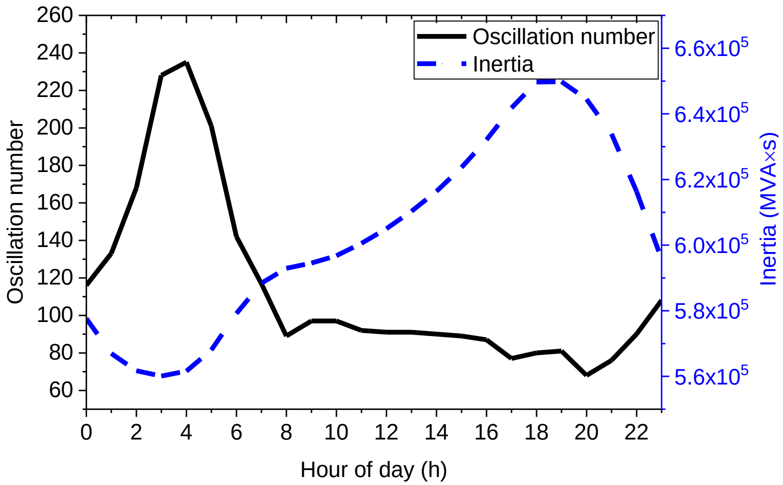
Ambient frequency variation at (a) 100% and (b) 50% inertia level

Machine-learning-based inertia estimation — extract informative features

- Correlation Between Inertia and Frequency Variation
  - The correlation coefficient between hourly occurrence of inter-area oscillations in WECC and hourly inertia is approximately 0.8



Oscillation occurrence distribution in one year

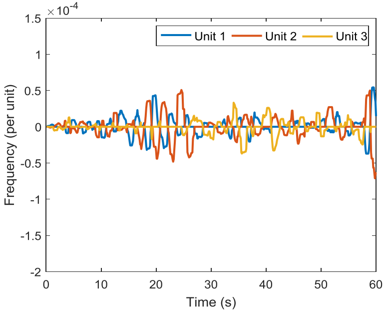


Correlation between inertia and oscillation occurrence

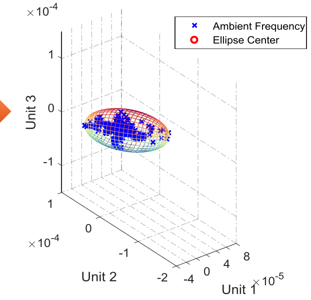
Machine-learning-based inertia estimation — extract informative features

- Feature Extraction Using Minimum Volume Enclosing Ellipsoid (MVEE)

100% inertia

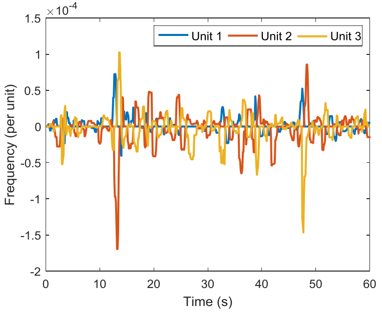


(a1)

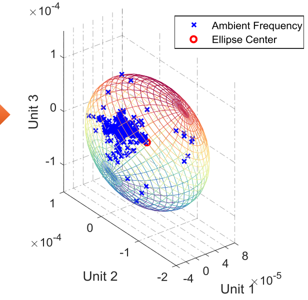


(a2)

50% inertia



(b1)



(b2)

Ambient frequency variation **Characteristic ellipsoids**

Graphic parameters of frequency ellipsoid at different inertia levels

Graphic parameters		100% inertia level	50% inertia level
Volume ($\times 10^{-13}$)		3.5	40
Eccentricity		0.81	0.93
Centers ($\times 10^{-6}$)	Unit 1	8.2	18
	Unit 2	-7.6	-47
	Unit 3	-1.7	-11
Projection of the longest semi axes ($\times 10^{-6}$)	Unit 1	36	-6.7
	Unit 2	-63	-109
	Unit 3	3.5	105

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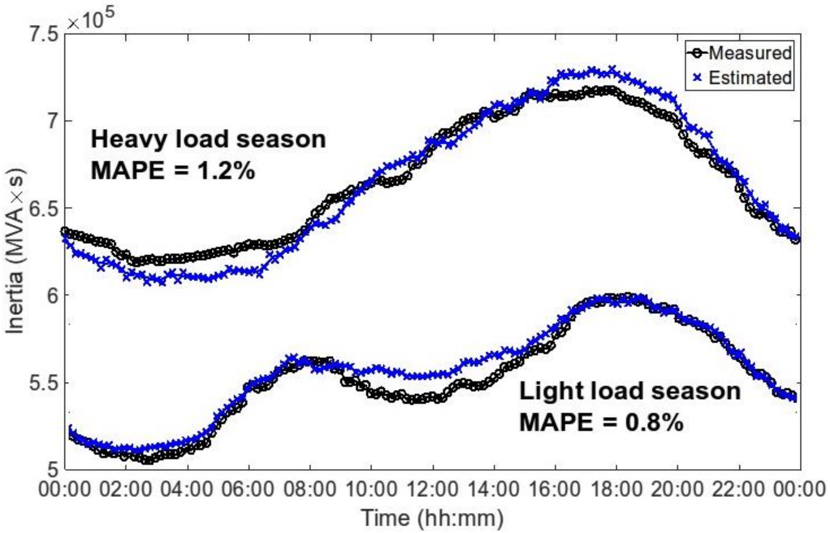
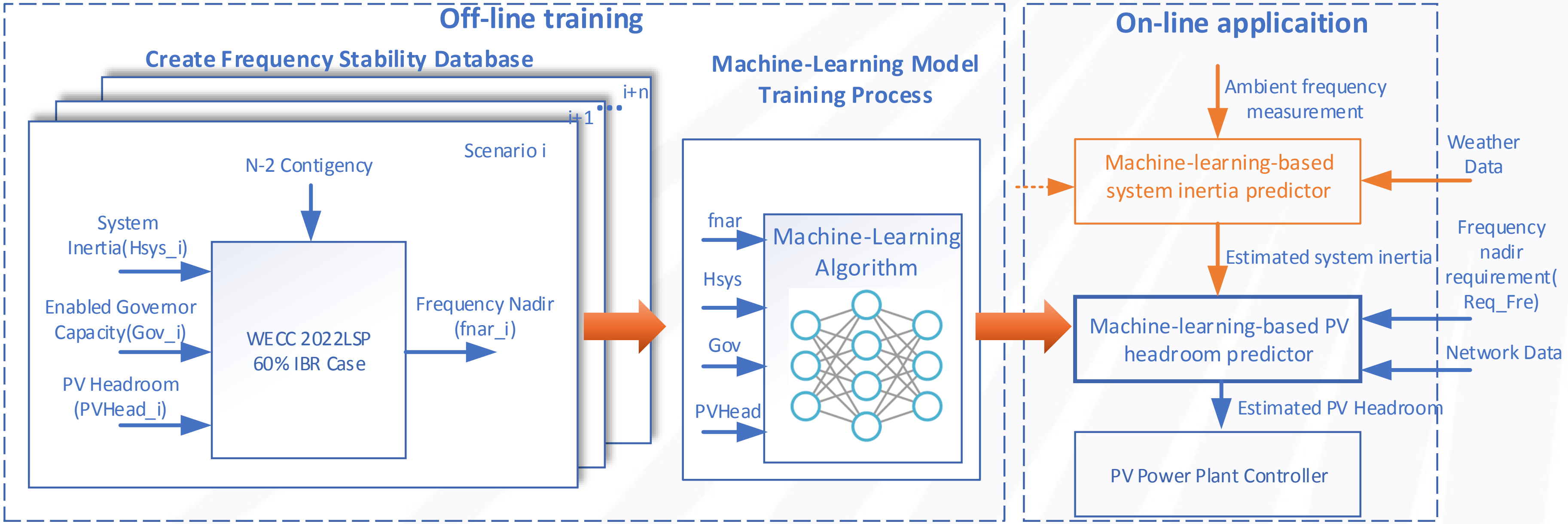
Machine-learning-based inertia estimation — accuracy test

- Performance Evaluation
  - Inertia estimation accuracy: mean Absolute Percentage Errors (APEs) of estimated inertia during heavy and light load seasons are all below 2%



Measured and estimated inertia during heavy and light load seasons

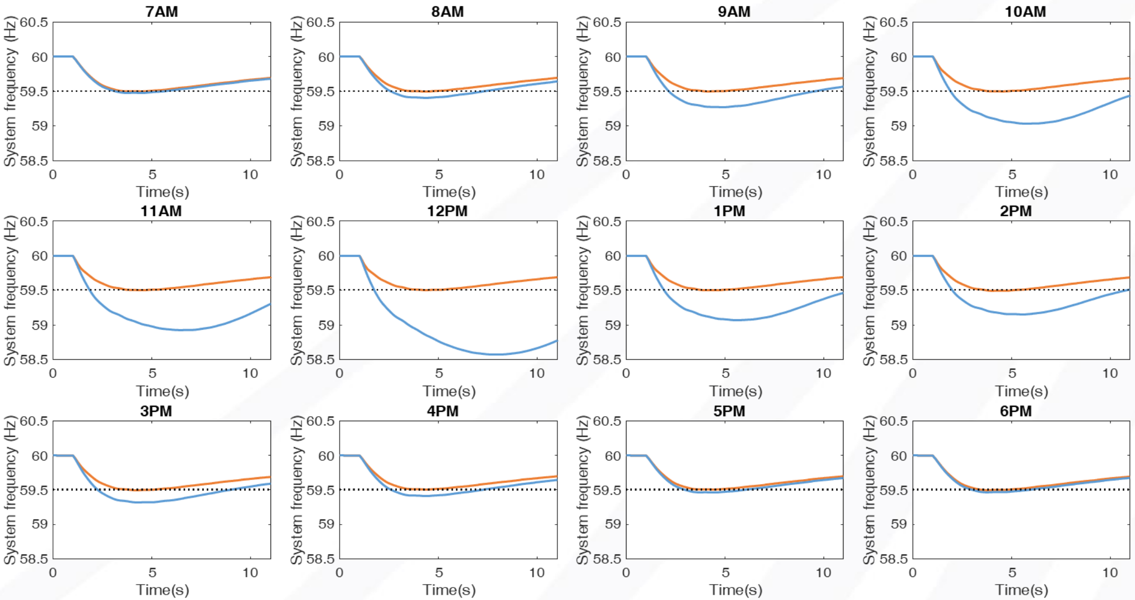
Flowchart of machine-learning-based PV frequency control



Flowchart of machine-learning-based PV frequency control

Scenario Study of a Typical Day with High PV Penetration

- Performance evaluation of smart frequency control
  - Frequency response using the proposed smart frequency control and not using smart frequency control.



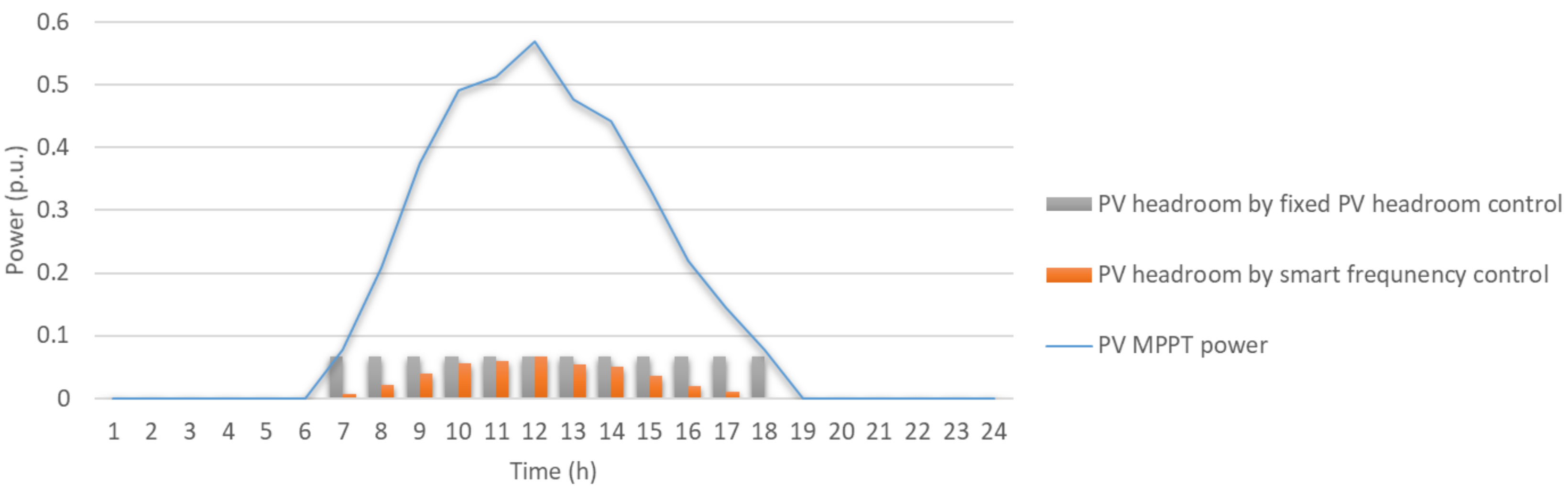
Frequency response **with** smart frequency control

Frequency response **without** smart frequency control

Frequency responses from 7AM to 6 PM

Scenario Study of a Typical Day with High PV Penetration

- PV headroom savings
  - Comparison between the proposed smart frequency control and the fixed headroom control on PV headroom savings: 50% (in the study day).



PV headroom values from the smart frequency control and fixed PV headroom control

Implement the smart PV frequency control schemes on GE's utility-level PV inverter

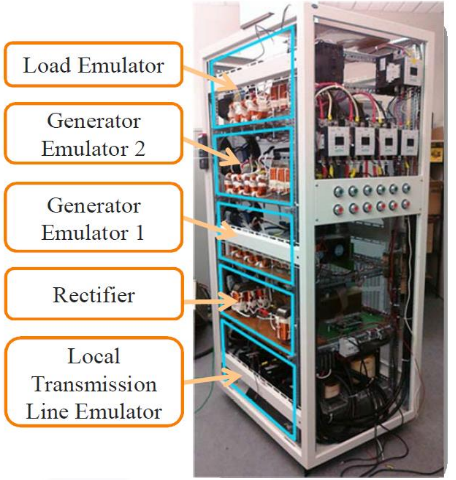
- Smart inverter frequency control evaluation system:
  - The inverter controller: MarkVIe based actual inverter control
  - The inverter and the grid: RTDS

GE Brilliance Solar Inverter HIL system

Test the smart PV frequency control scheme in CURENT Hardware Testbed.

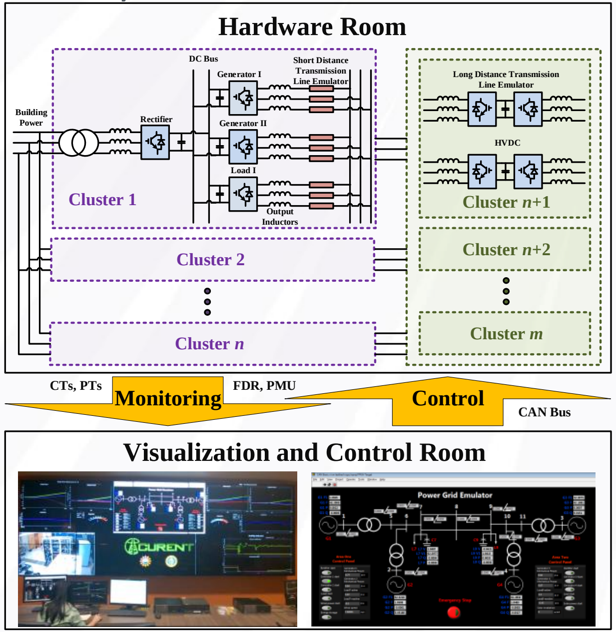
- CURENT HTB Introduction
  - CURENT HTB consists of modular and reprogrammable three-phase converters and a reconfigurable structure to emulate large scale power systems.

HTB Hardware room



Configuration of one HTB cabinet

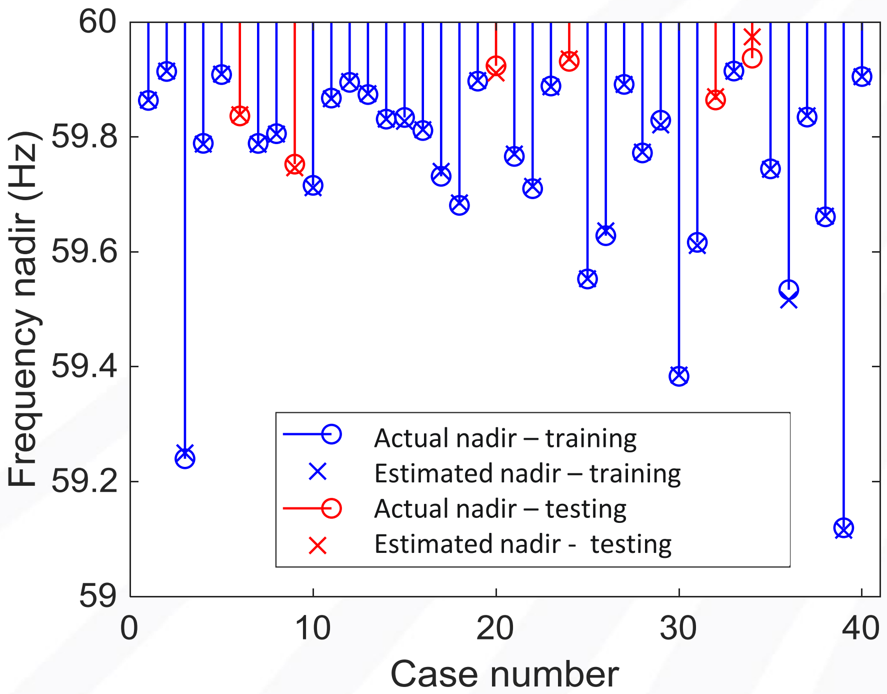
CURENT Hardware Testbed



Architecture of the CURENT Hardware Testbed

Test the smart PV frequency control scheme in CURENT Hardware Testbed.

- Machine learning based nadir prediction in HTB



Frequency nadirs comparison between machine learning prediction results and testbed results

Challenges

- **Model extreme high PV penetration grids**
  - The capability to model real-world power grids at 90 to 100% inverter penetration
- **Study abnormal operation conditions in extreme high PV penetration conditions;**
  - Characteristics requirements of grid forming inverters.
  - Inverter interactions during faults and system transient/dynamic conditions.
- **Hardware validation and field test**
  - Flexibility of testing (actual power grid configurations are not totally free to manipulate)

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