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Hierarchical Controller Design for Engaging HPWHs to Provide Primary Frequency Regulation

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Project objectives

- Provide a framework to facilitate large-scale deployment of frequency responsive devices
- Systematically design decentralized frequency-based load control strategies for enhanced stability performance
- Ensure applicability over wide range of operating conditions while accounting for unpredictable end-use behavior and physical device constraints
- Test and validate control strategy using large-scale simulations

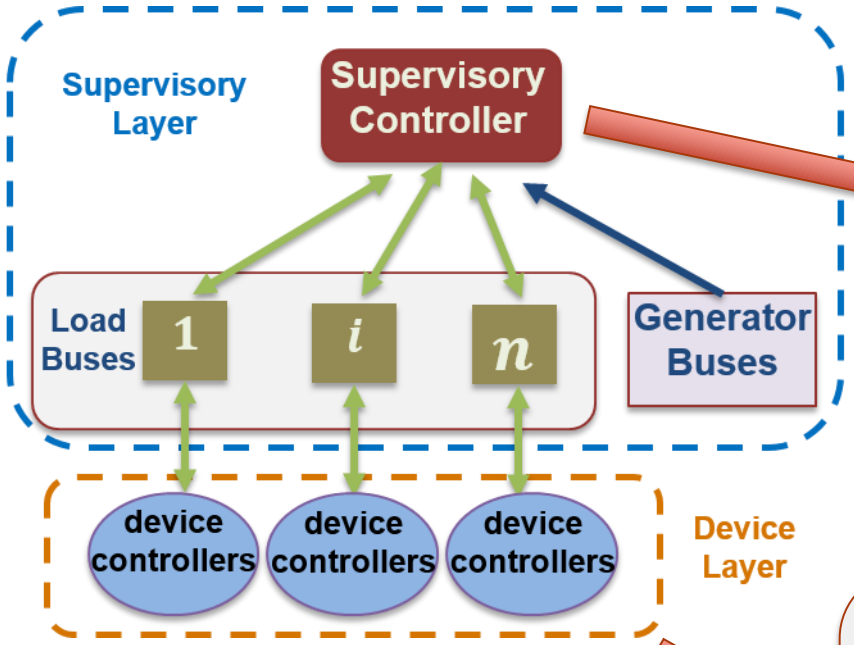
NERC BAL-003-1 Standard

- "To require sufficient Frequency Response from the Balancing Authority (BA) to maintain Interconnection Frequency within predefined bounds by arresting frequency deviations and supporting frequency until the frequency is restored to its scheduled value."[1]
  - System-wide requirement: Interconnection Frequency Response Obligation (IFRO)
  - Area-wide requirement: Frequency Response Obligation (FRO)
  - IFRO calculated based on contingencies and FRO calculated as a portion of IFRO to be met by areas

- Compliance with FRO and IFRO measured with annual Frequency Response Measure (FRM), which is calculated from system event data

[1] : Standard BAL-003-1 — Frequency Response and Frequency Bias Setting

GFA-based hierarchical frequency control design (GHFC)



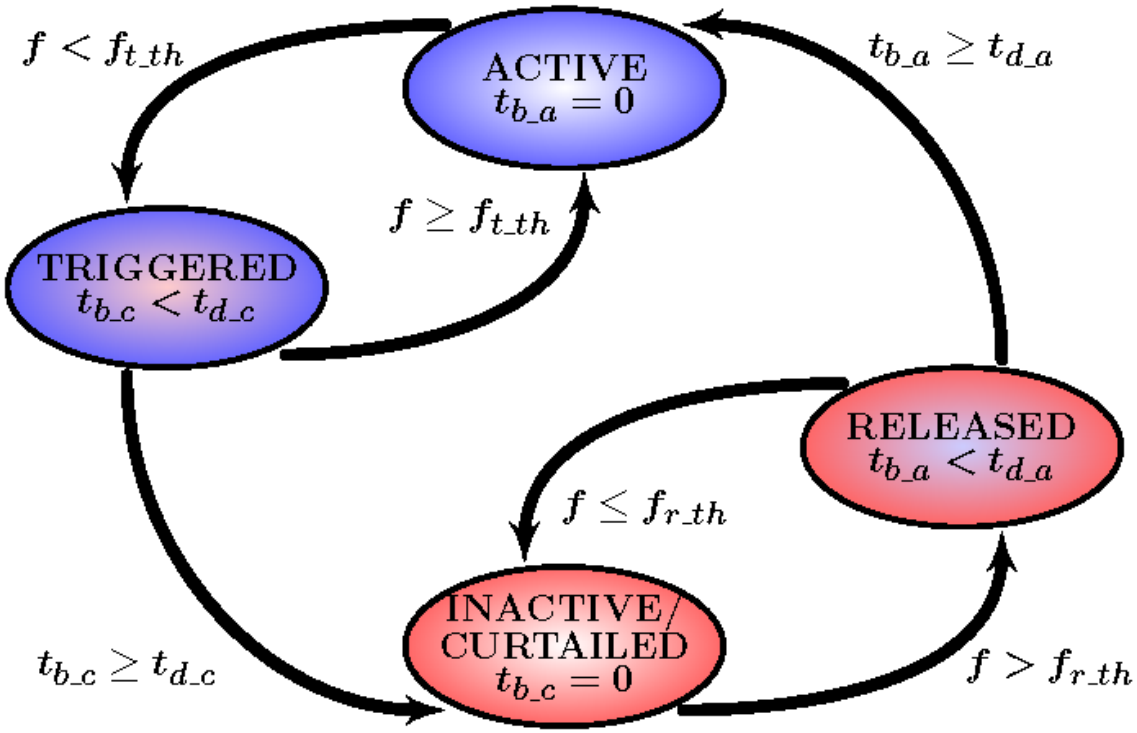
Every 10 to 15 minutes

- Collect information on current operating condition of each individual device
- Design load control gains used to specify the desired power modulation of the aggregate load response
- Broadcast control gains and system states to individual devices

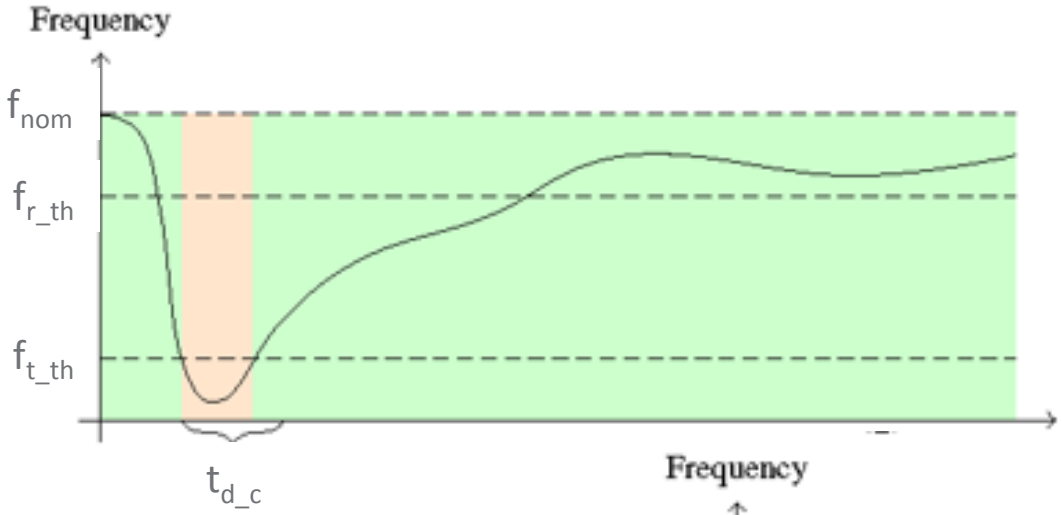
Real time

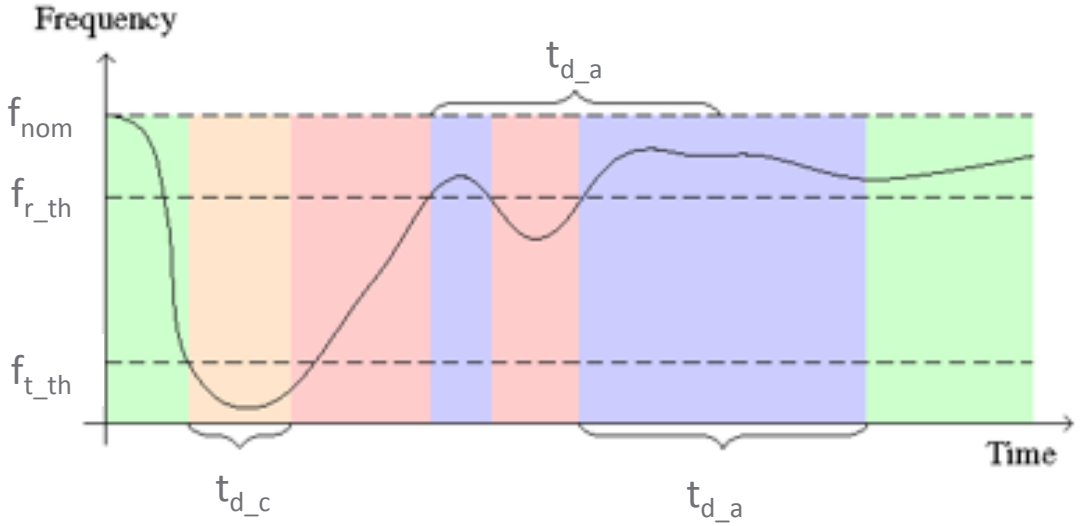
- Respond independently in such a way that the aggregate response will meet desired power modulation
- Respect physical device constraints

Grid Friendly Appliance Control Logic

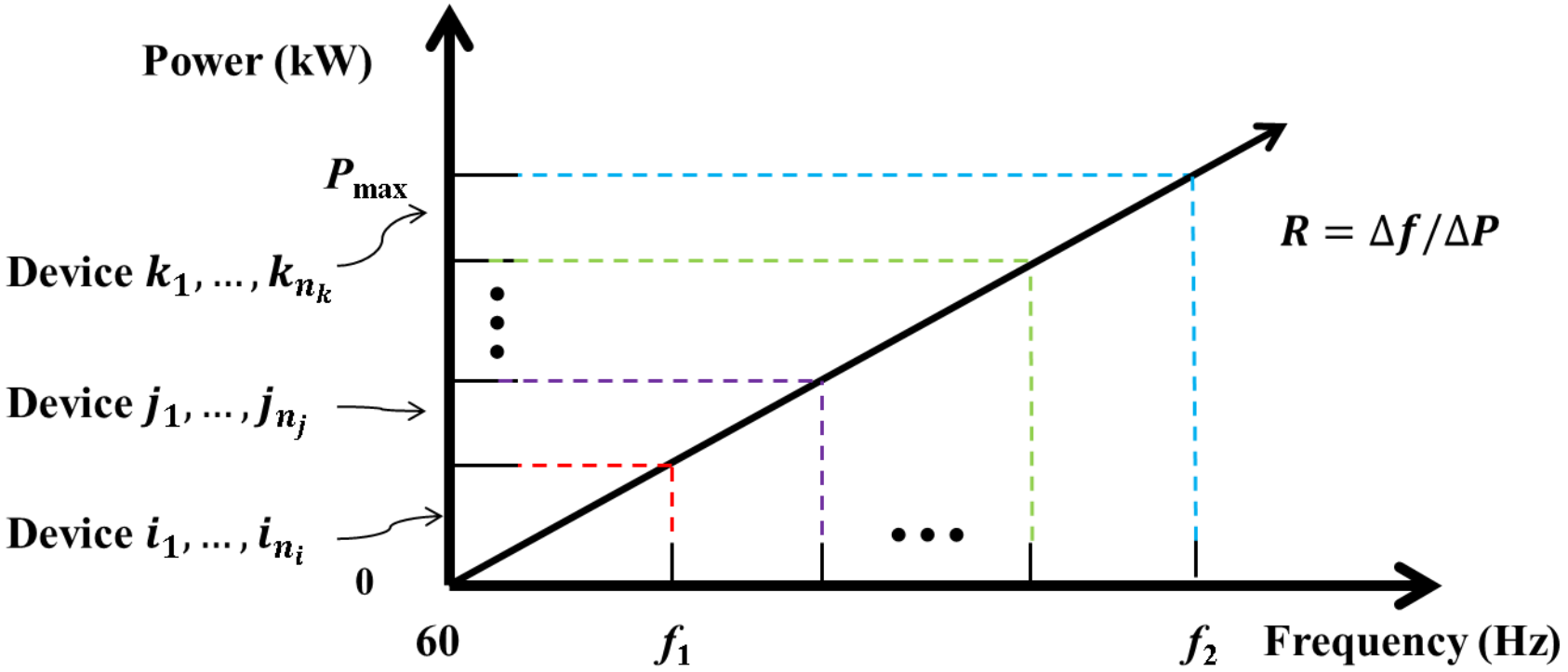


Grid Friendly Appliance Control Logic Example





Supervised frequency threshold determination

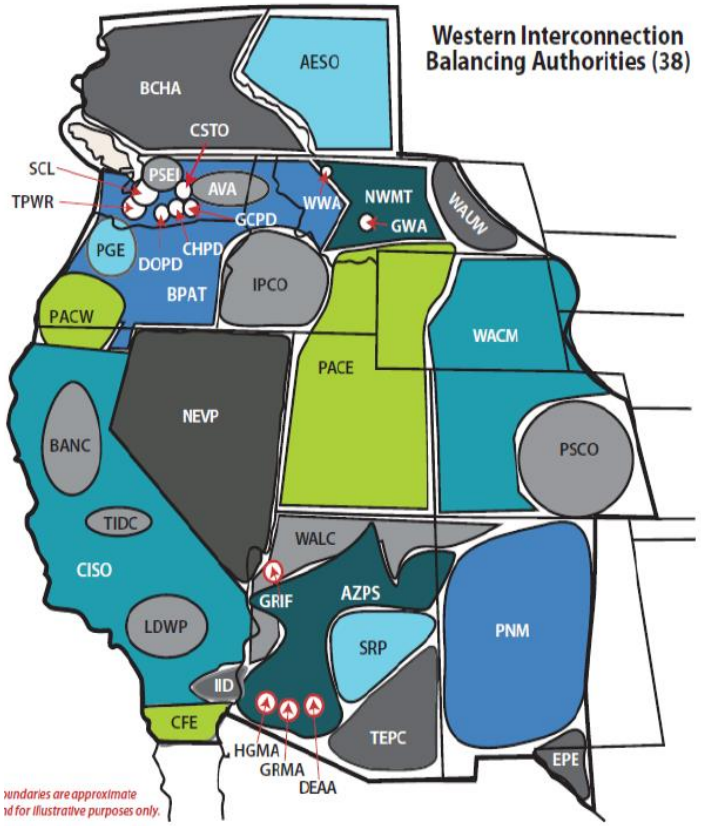


WECC Test System

- WECC system simulated in PowerWorld software with User Defined Model for responsive loads

- WECC system
  - # of buses: ~20,500
  - # of generators: ~3,900
  - # of transmission lines: ~16,400
  - # of loads: ~10,900

- WECC high summer 2015
  - Total load: ~159 GW
  - Contingency: loss of ~2700 MW generation in the South



Test Scenarios

- Three main scenarios:
  - (S1) low availability of controllable load, about 900,000 water heaters
  - (S2) high availability of controllable load, about 6.2M water heaters
  - (S3) extreme availability of controllable load, about 13M water heaters
- Three sub-cases for each scenario:
  - (A) No control
  - (B) GHFC without supervisory layer
  - (C) GHFC with supervisory layer

System-wide impacts of GHFC Low availability

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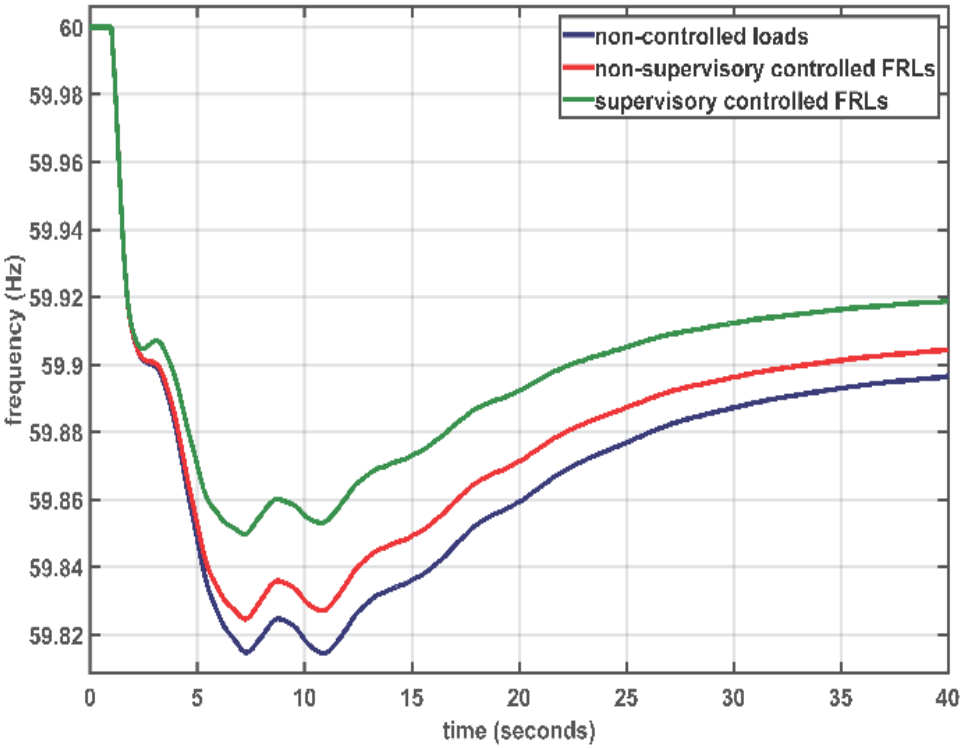
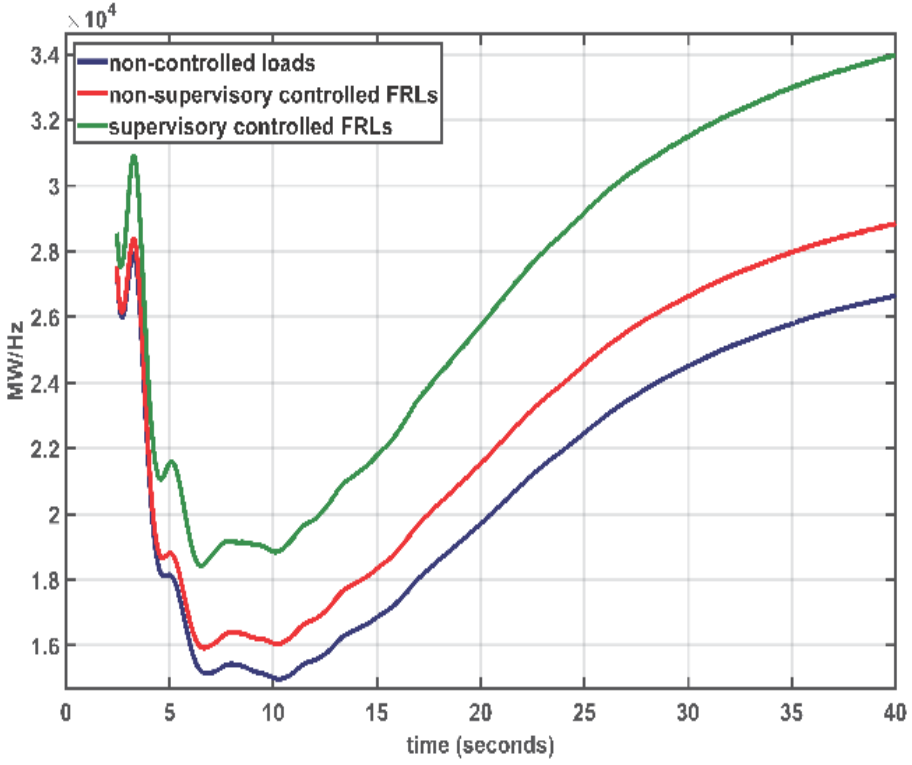
Frequency Response (Hz)



System Response (MW/Hz)



System-wide impacts of GHFC
High availability

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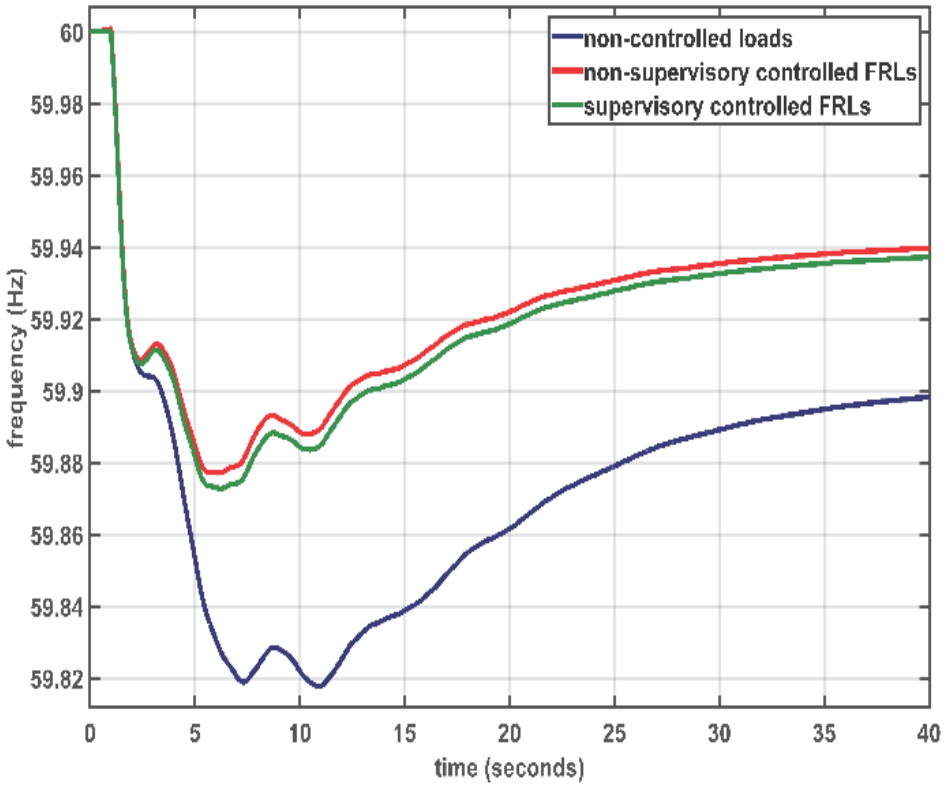
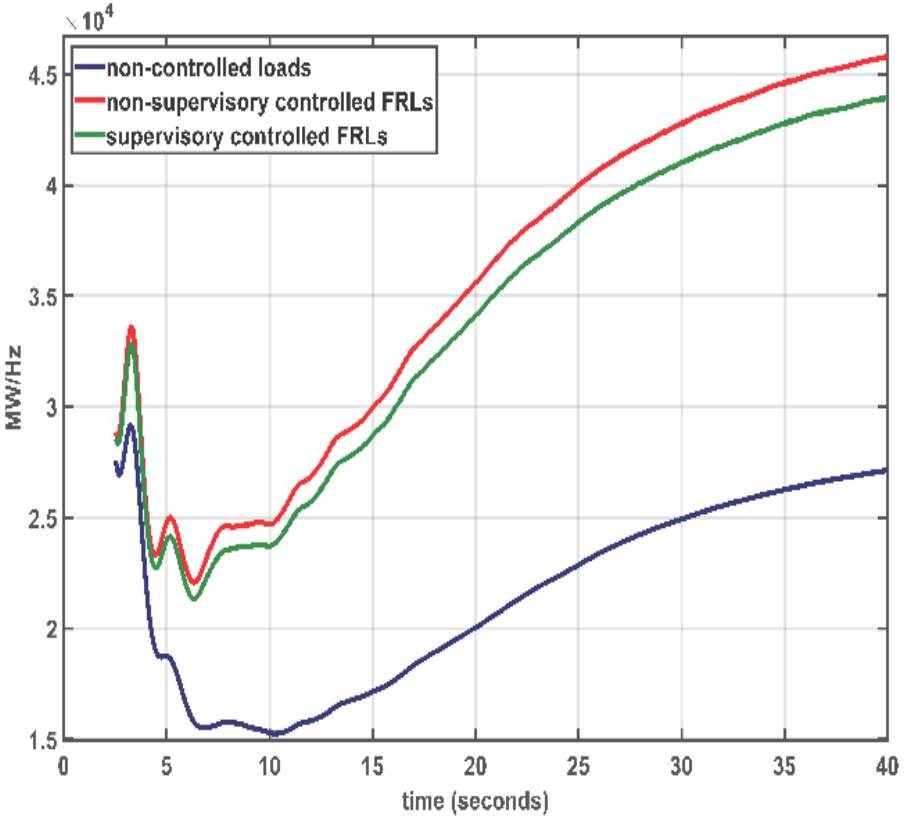
Frequency Response (Hz)



System Response (MW/Hz)



System-wide impacts of GHFC Extreme availability

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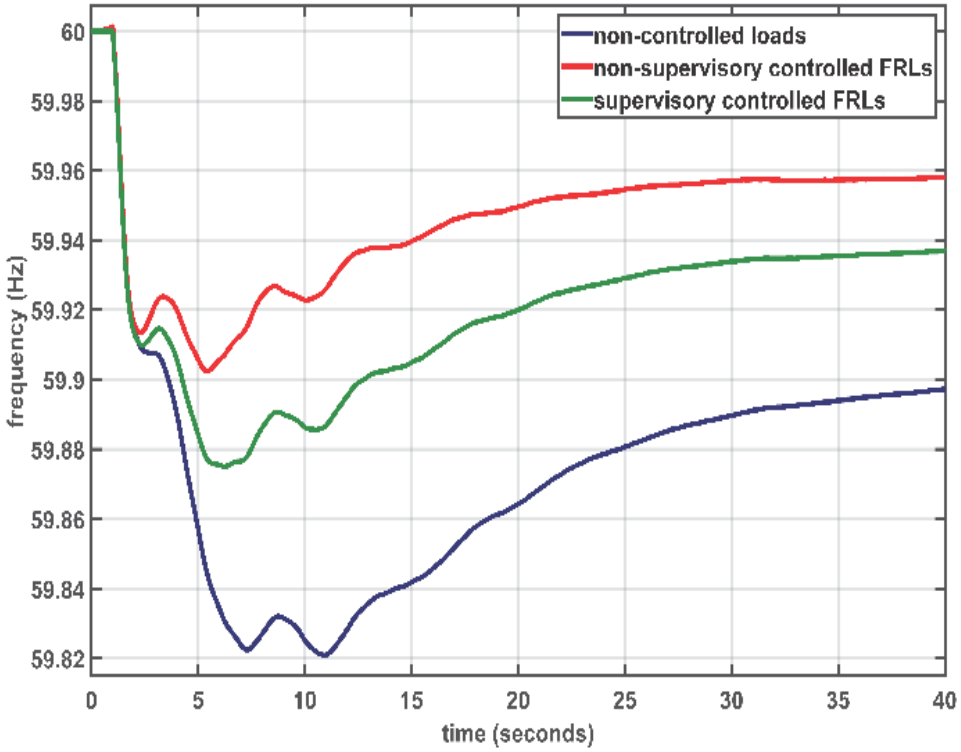
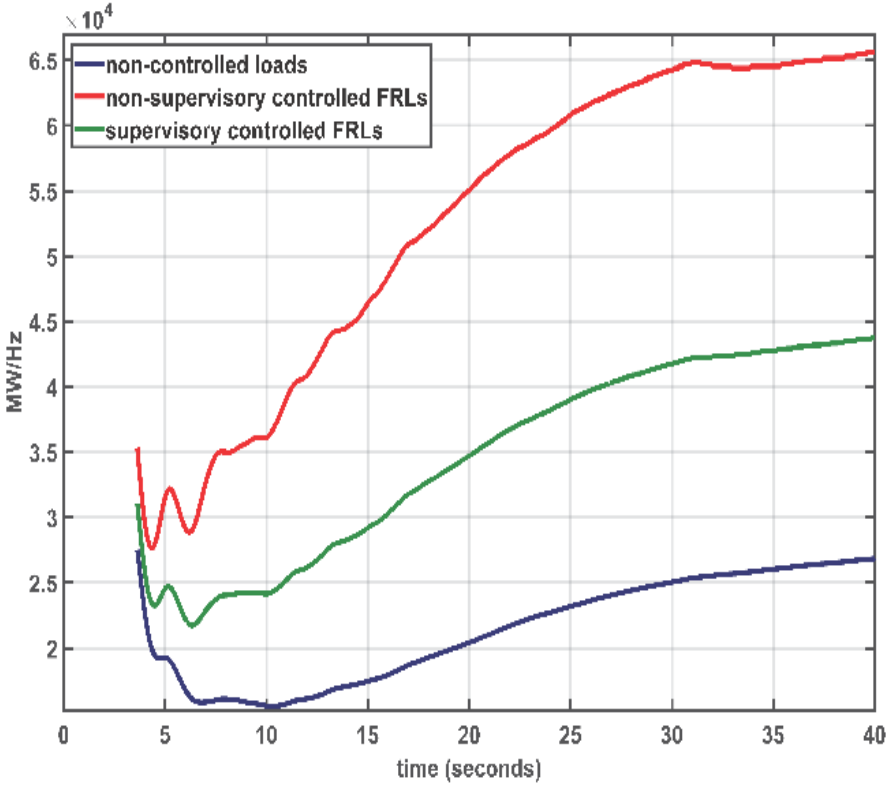
Frequency Response (Hz)

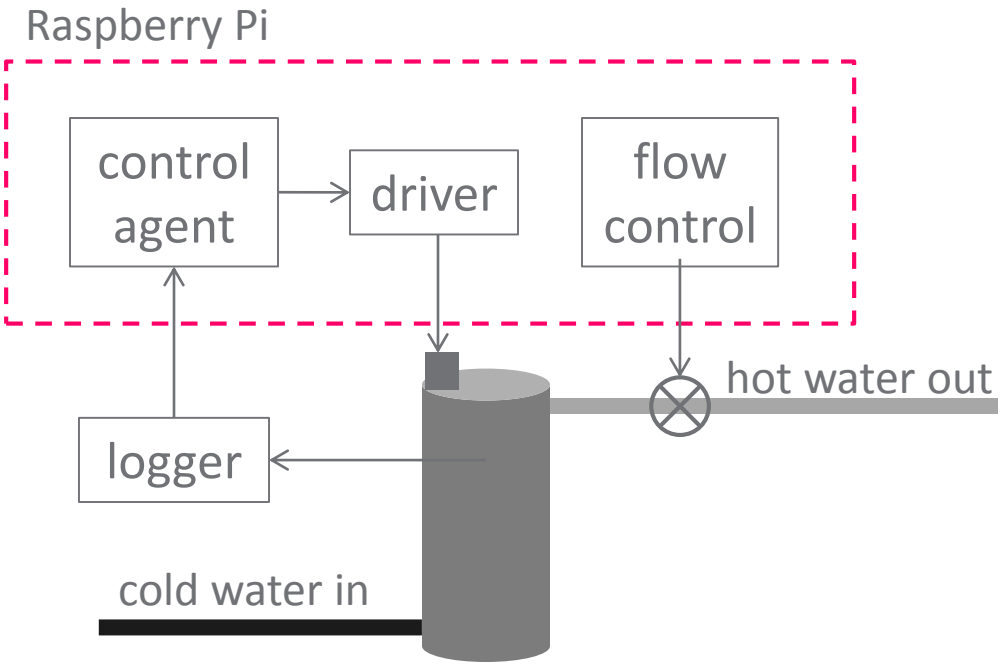


System Response (MW/Hz)

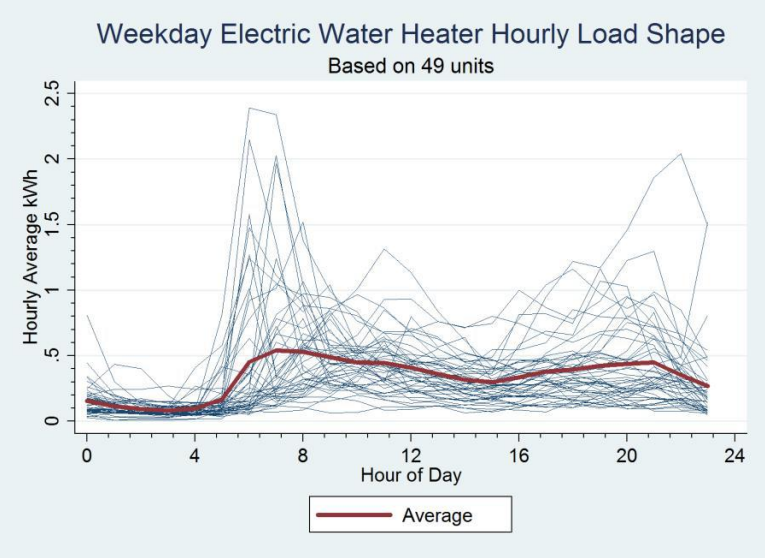


Hardware Testing and Model Validation

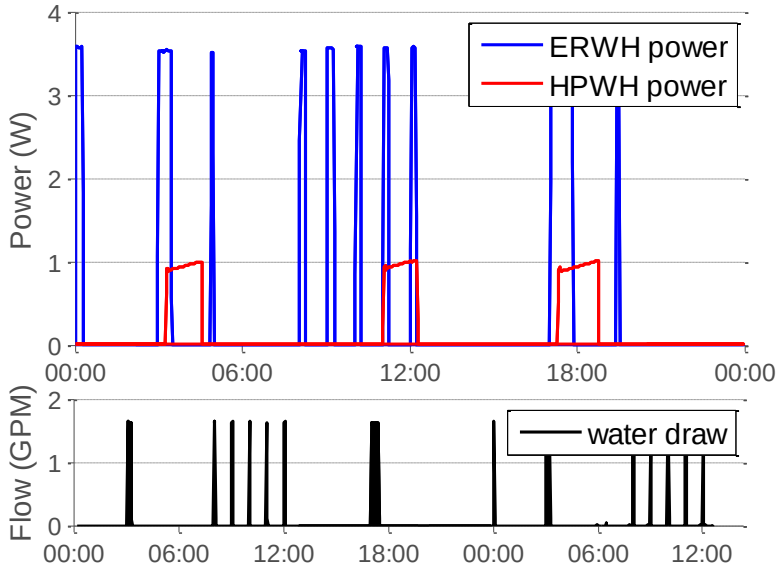
- Perform hardware testing in a laboratory setting to
  - Improve and calibrate existing load models
  - Provide recommendations for appliances providing primary frequency control



Water Heater Load Profiles



RBSA 2014



- Leverage prior studies of water draw profiles
- Develop load shapes for populations of water heaters
- Determine device load response to external signal

Conclusion

- Control strategy implemented and tested on WECC 2015 scenario
- Improved frequency recovery in terms of steady state error and maximum frequency deviation
- Presented that load control could be used as a additional resource to provide primary frequency response
- Supervisory droop characteristics can be adapted based on desired penetration and changing operating conditions
- Calibrated models and determined response time by performing experiments on physical devices