DOE/OE Transmission Reliability R&D Load as a Resource (LaaR)

Frequency responsive demand

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Project objectives

- Provide a framework to facilitate large-scale deployment of frequency responsive end-use 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 and field demonstrations
- Create a level-playing field for smart grid assets with conventional generators

Recap –FY12 activities

- Extensive studies demonstrating potential of autonomous frequency load control performed on WECC model in PSLF
- Control strategies assumed **fixed** proportional response not considering changing bulk system conditions
- No systematic way of designing gains to ensure stability over wide range of operating conditions
- Simplistic end-use load models employed ignoring end-use behavior and physical device constraints

Recap –FY13 activities

Task 1: Proposed hierarchical primary frequency control strategy

- Supervisory controller design based on robust control theory to ensure stability over a wide range of operating conditions.
- Control gains updated every few minutes allows for adaptation to time-varying system operating conditions
- Local load response rules incorporate physical device constraints and respect end-use behavior
- Studies performed on 16 machine IEEE test system to demonstrate proof-of-concept

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Recap –FY13 activities contd.

Task 2: Studied system impacts of Grid-Friendly™ Appliances for under-frequency load shedding

- Location of GFAs affects system stability performance
- Impact of location is coupled with time delay
- Need further investigation into how many GFAs to deploy across the system
- Develop systematic GFA control design such that aggregate response mimics generator "droop" like response

FY14 tasks

Task 1: Modify design of hierarchical control strategy

- Responds to only frequency deviation
- Respect actual response capability of load population
- Allow for simple and scalable implementation

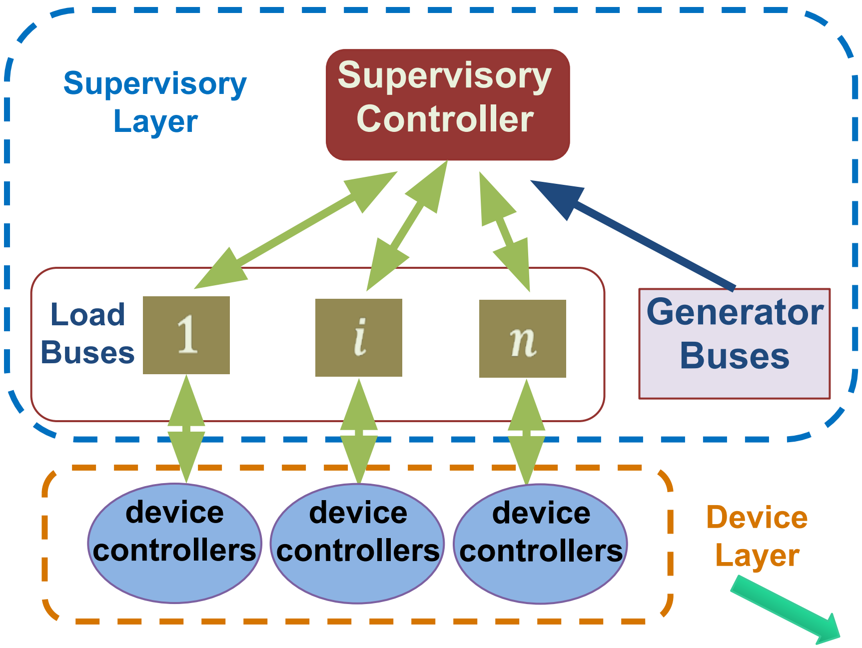
Task 2: Validation of modified control strategy on large-scale systems

- Implement on WECC model in PowerWorld

Task 3: Modify GFA design to mimic droop response

TASK 1: EXTEND DESIGN OF HIERARCHICAL CONTROL STRATEGY

Hierarchical control strategy



Every few minutes

- Collect information on current operating condition of each participating device
- Compute desired load bus control gains
- Broadcast control gains and system states to individual devices

Real time

- Respond independently to meet desired aggregated power consumption
- Respect end-use physical constraints

Supervisory Control Gain Design

- Desired aggregated response $\Delta P_i = k_i\left(f_i(t_k) - 60hz\right)$

$$k_i = K_{sys} * K_{bus} = \frac{pct_{max,load} P_{load,sys}}{\Delta f_{min}} * \frac{pct_{cont,ON}\ P_{cont,\mathrm{i}}}{P_{cont,sys}}$$

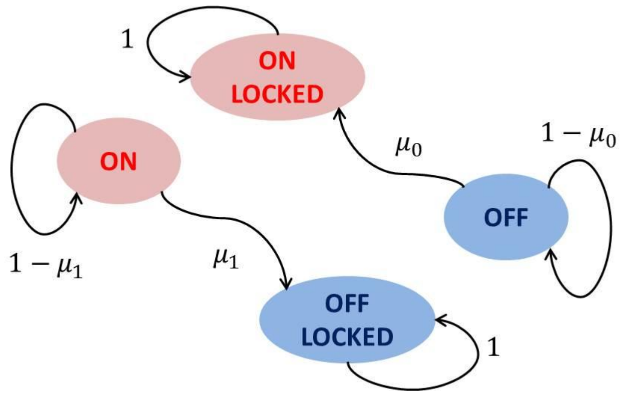
- Update gains only needed when there are significant changes in system load and/or controllable load

Δf_{min} —frequency deviation threshold that activates load control before emergency under-frequency load shedding
$pct_{max,load}$ —maximum percentage of total system load that should act atΔf_{min}
$pct_{cont,ON}$ —percentage of controllable load in ON state
$P_{cont,sys}$ —total controllable load available system-wide
$\mathrm{P}_{cont,i}$ —total controllable load available at a substation bus *i*
$P_{load,sys}$ —total load available system-wide

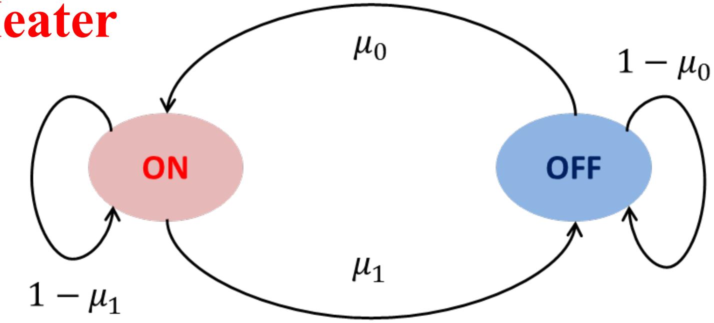
Device Layer Control

- Consider thermostatically controlled loads (HVACs, water heaters, etc.)

HVAC



Water Heater



$$\boldsymbol{p}(t_k) = \begin{bmatrix} p_{\mathrm{ON}}(t_k) \\ p_{\mathrm{OFFLCK}}(t_k) \\ p_{\mathrm{OFF}}(t_k) \\ p_{\mathrm{ONLCK}}(t_k) \end{bmatrix} \quad \boldsymbol{A}(t_k) = \begin{bmatrix} 1-\mu_1(t_k) & 0 & 0 & 0 \\ \mu_1(t_k) & 1 & 0 & 0 \\ 0 & 0 & 1-\mu_0(t_k) & 0 \\ 0 & 0 & \mu_0(t_k) & 1 \end{bmatrix}$$

$$\boldsymbol{p}(t_k) = \begin{bmatrix} p_{\mathrm{ON}}(t_k) \\ p_{\mathrm{OFF}}(t_k) \end{bmatrix} \quad \boldsymbol{A}(t_k) = \begin{bmatrix} 1-\mu_1(t_k) & \mu_1(t_k) \\ \mu_0(t_k) & 1-\mu_0(t_k) \end{bmatrix}$$

- Derive Markov chain model $\boldsymbol{p}(t_{k+1}) = \boldsymbol{A}(t_k)\boldsymbol{p}(t_k)$
- Calculate switching probabilities μ_0 and μ_1 based on desired power reference from supervisory control layer $\Delta P_i(t_k) = k_i(f_i(t_k) - 60Hz)$

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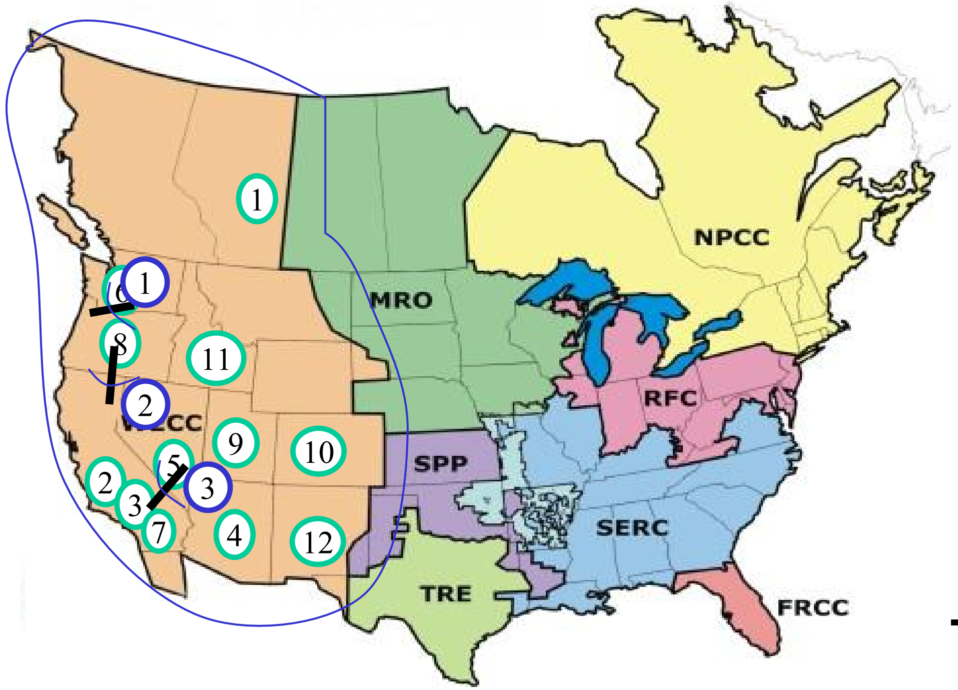
TASK 2: VALIDATION OF MODIFIED CONTROL STRATEGY ON LARGE-SCALE SYSTEMS

PowerWorld implementation

- User defined model for loads implemented in PowerWorld (transient stability application module) using VS C++ 2010 as a DLL
- Implemented as modified WSCC load model (ZIP load)
- Active power load defined based on:
  - Controller model: Markov chain with controlled probabilities based on $\Delta P_i = k_i(f_i(t_k) - 60hz)$
  - Impedance part of ZIP load is controlled only (OK for water heaters, crude approximation for HVAC)
- Reactive power changes as portion of changes in active power to represent effect of reactive power consumptions of distribution networks and substations as the end use load changes

WECC test scenarios

- WECC system
  - # of buses: 20,000
  - # of generators: 3,900
  - # of transmission lines: 16,000
  - # of loads: 10,800
- 12 loads monitored
- 3 interties monitored



- 140 loads are controlled
  - Total 40,100 MW
  - Test cases with 30% and 100% controllable
  - Test cases with initial state of loads: 40% and 80% in on state
- WECC high summer 2014
  - Total load: 167 GW
  - Total generation output: 173 GW
- WECC low winter 2022
  - Total load: 109 GW
  - Total generation output: 113 GW

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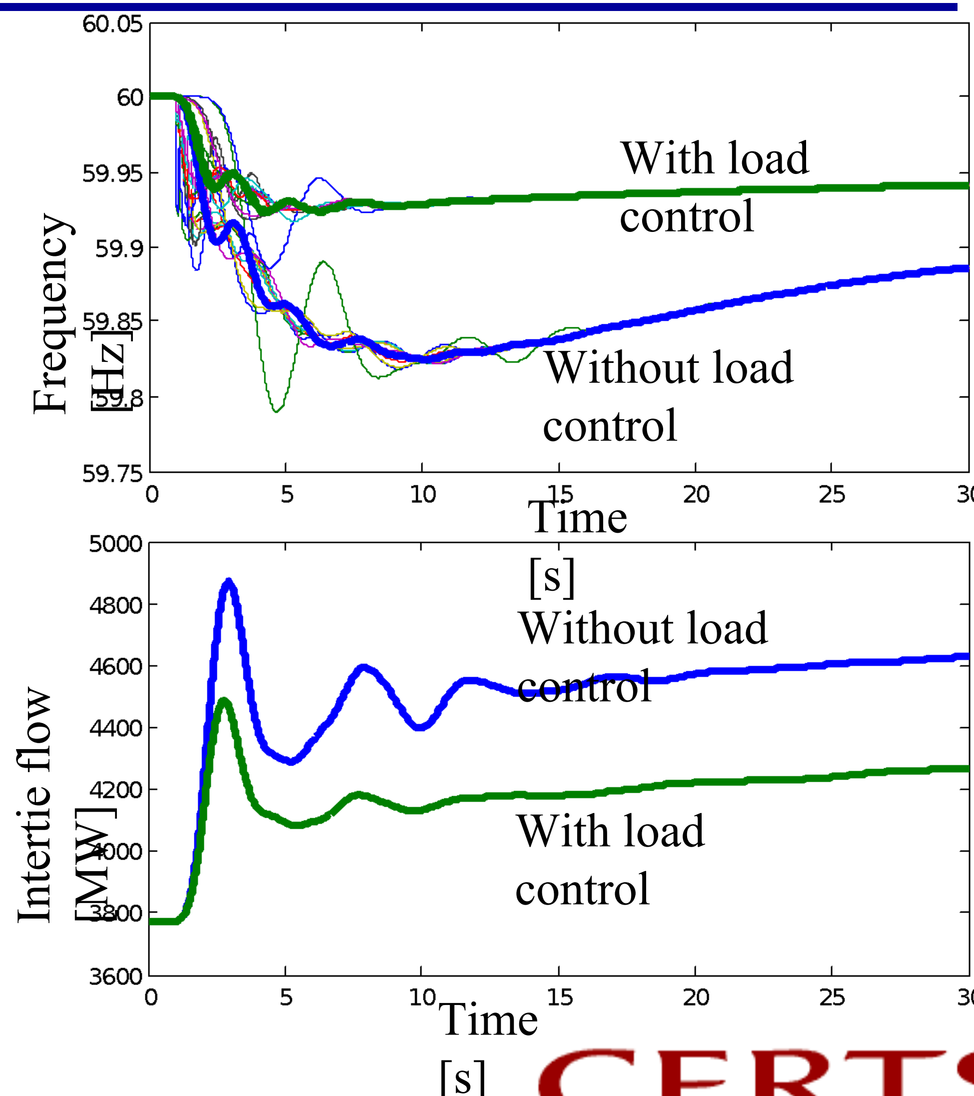
WECC with and without control

- WECC high summer 2014 case considered
- Better frequency recovery in terms of steady state error and maximum frequency deviation
- Less transmission capacity needed for PFC in intertie 2 (North to South transfer)



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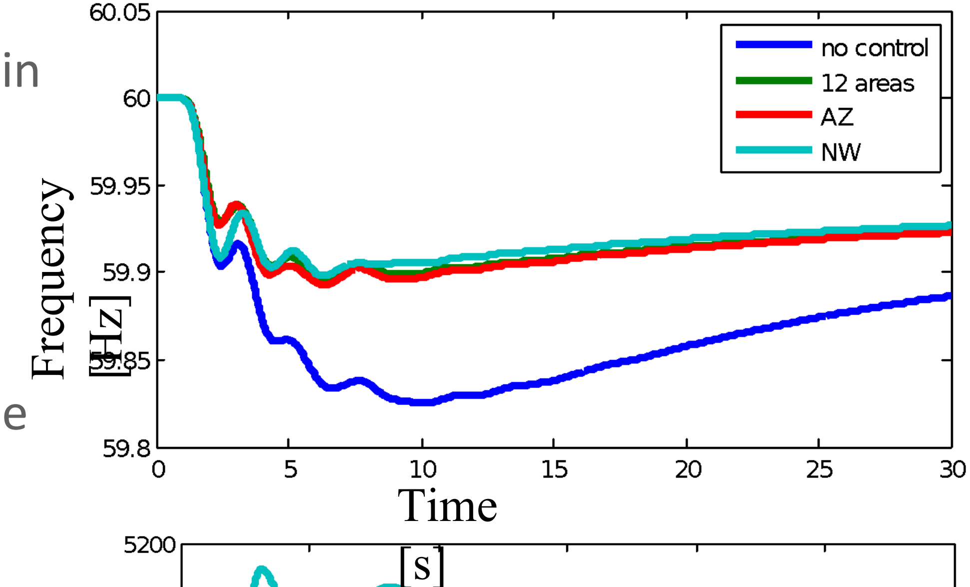
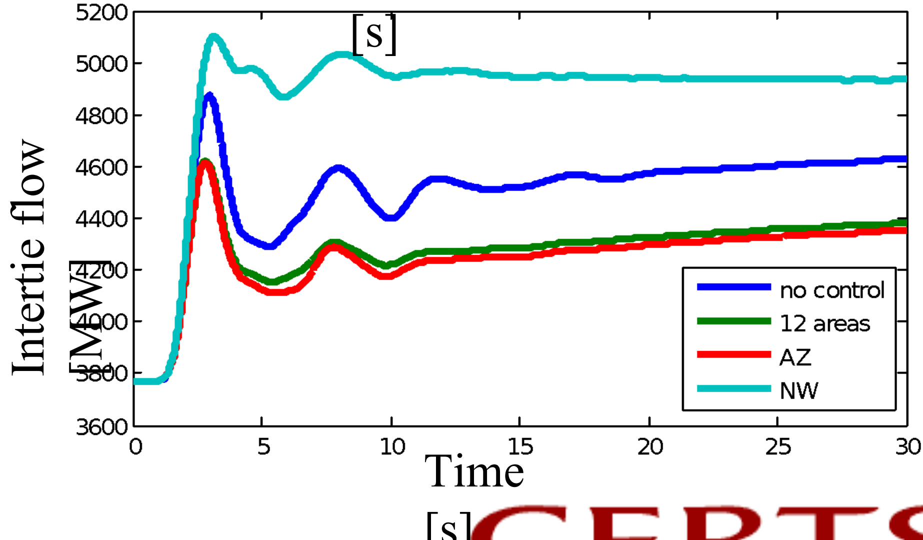
Sensitivity to location of controllable loads

- Controllable load concentrated in different locations:
  - Arizona (AZ)
  - Northwest (NW)
  - Distributed (12 areas)
- Disturbance located South of the system
- Intertie power flow response depends on relative location of disturbance and load/generation providing PFC
- Load control could be used as additional resource in areas with lack of generation, like south of WECC in summer





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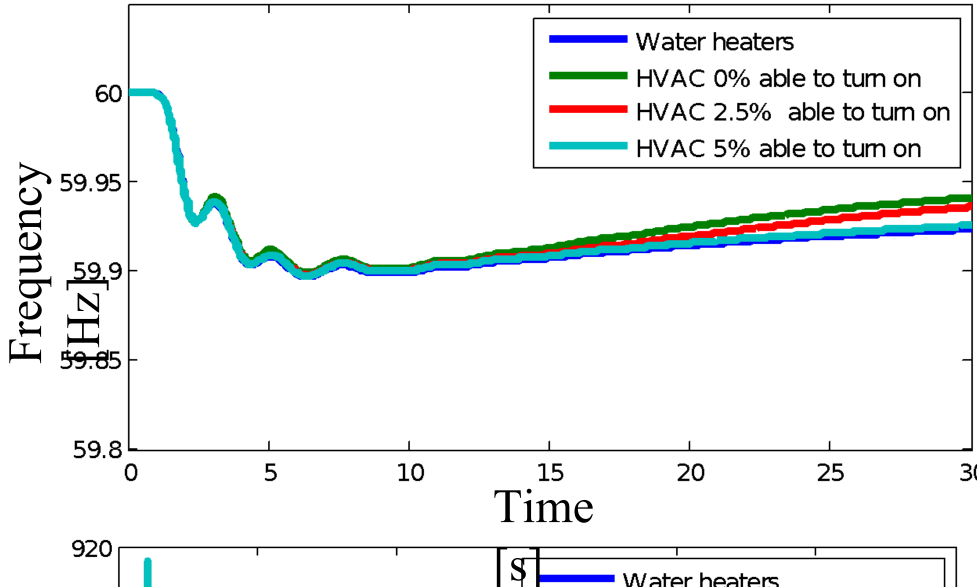
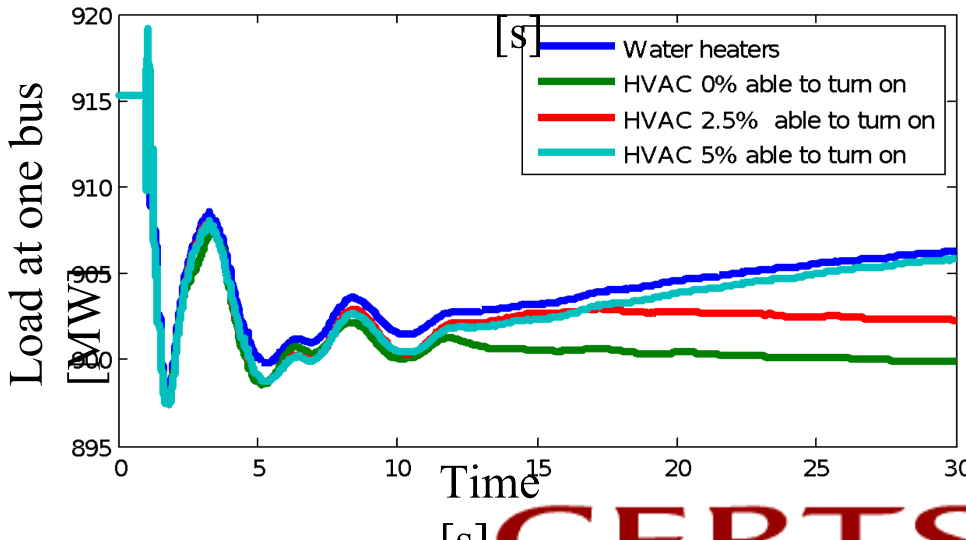
Sensitivity to type of loads

- HVAC loads compared with water heaters
  - HVAC lock out time modeled
  - Different % of HVAC in OFF state that can be turned back ON when frequency recovers
- HVAC cycle dynamics affect steady-state frequency and has a high impact on bus load response





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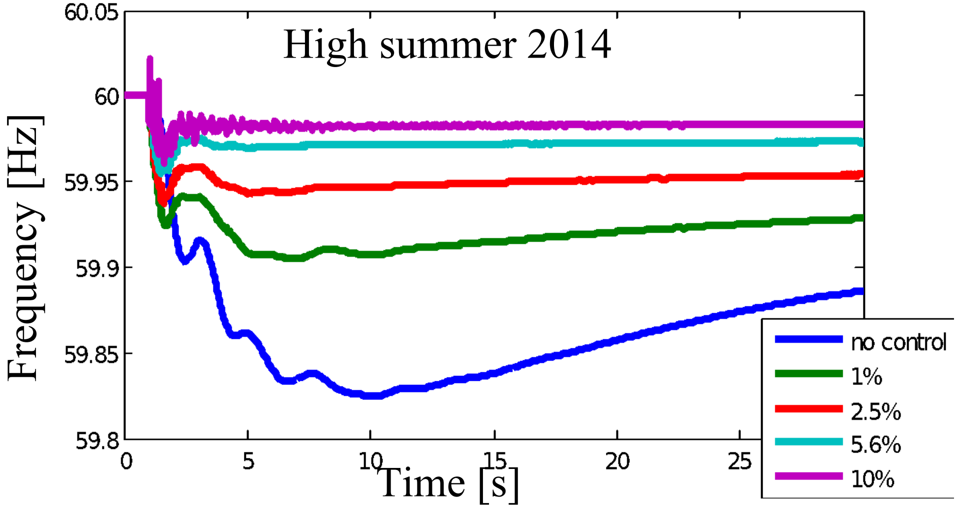
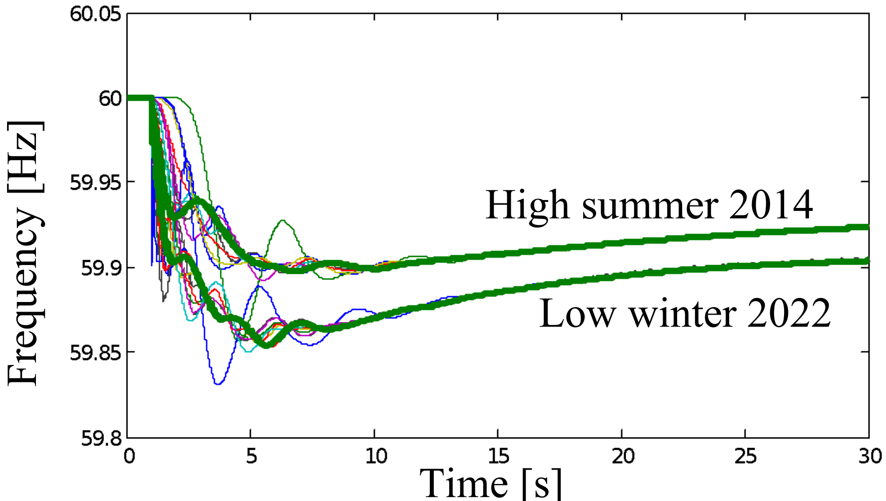
Sensitivity to control gain parameters

- High penetration of controllable load increases gain which decreases steady state error & improves transient response
- Large gains (10% penetration) produces "chattering" associated with discrete nature of implementation
- 1% penetration case also tested in future case of 2022 obtaining acceptable performance





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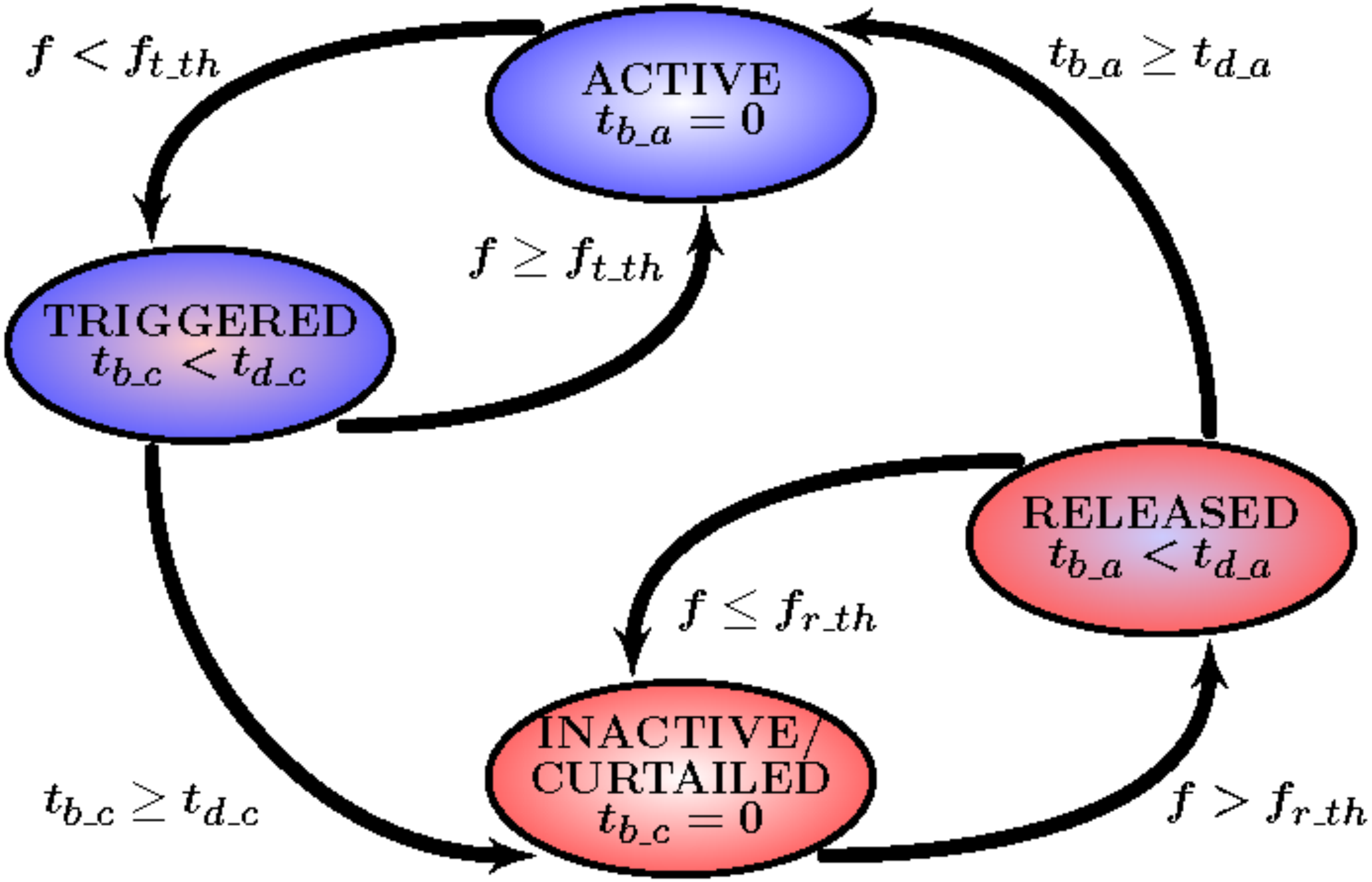
Conclusions -Tasks 1& 2

- Control strategy implemented and tested on WECC 2014 and 2022 scenarios
  - Improved frequency recovery in terms of steady state error and maximum frequency deviation
  - Intertie power flow response depends on relative location of disturbance and responsive load/generation
- Load control could be used as additional resource in areas with lack of generation (e.g. south of WECC in summer)
- Dynamics of different types of end-use loads (i.e. HVAC vs. water heaters) affect control performance
- Control gain can be adapted based on desired penetration and changing operating conditions

TASK 3: MODIFY GFA DESIGN TO MIMIC DROOP RESPONSE

Grid Friendly Appliance Control Logic

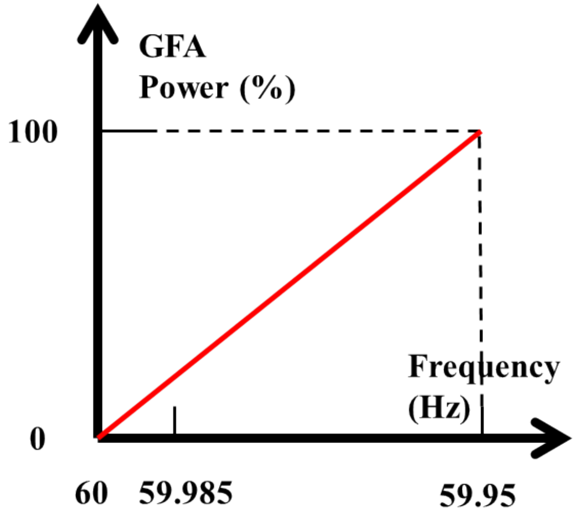


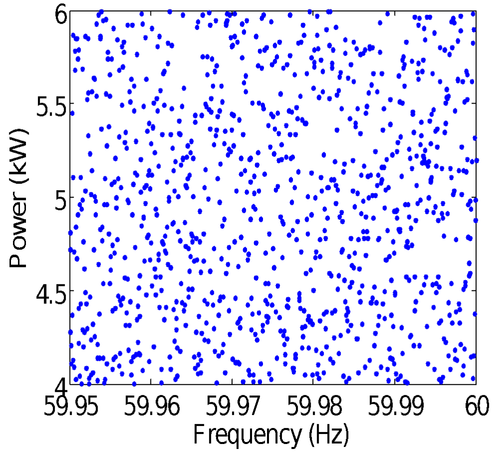
Controller Design and Analysis

- Cutoff frequency f_{t_th} of each GFA controller is randomly selected from prescribed frequency range between 59.95 Hz and 59.985 Hz
- Autonomous response may not mimic droop-like response in practice
  - Cutoff frequencies of GFAs currently ON may not be uniformly distributed
  - Power of each GFA currently ON can be quite different

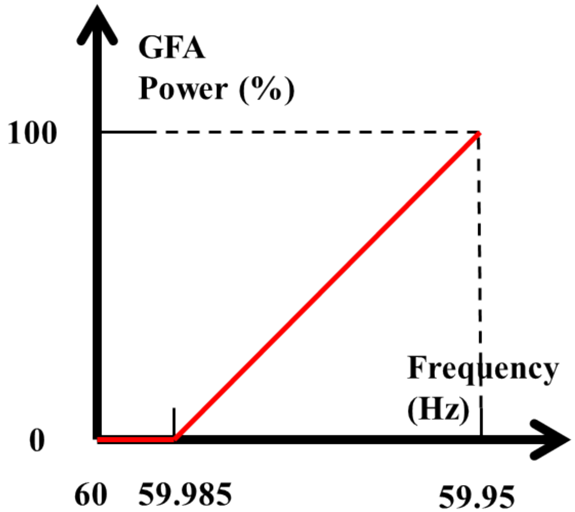
Power reduction vs frequency deviation –Normal case

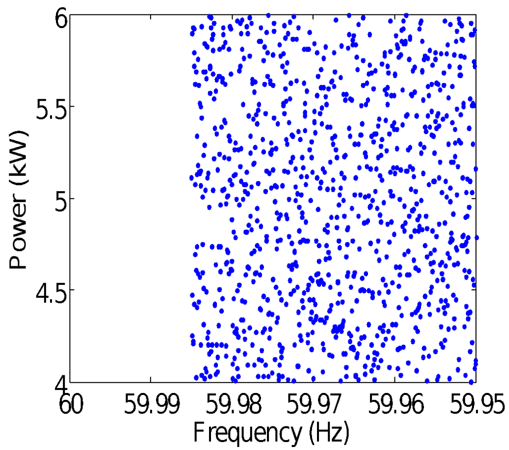
Desired behavior (droop-like)





Normal behavior (cutoff frequencies are uniformly distributed)





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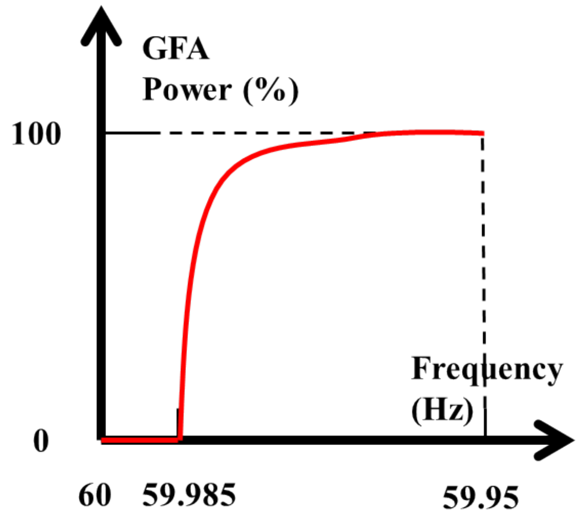
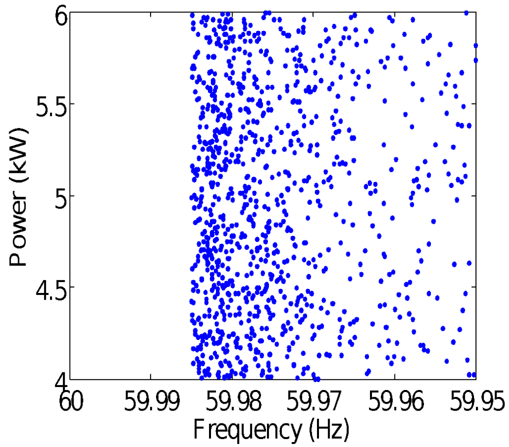
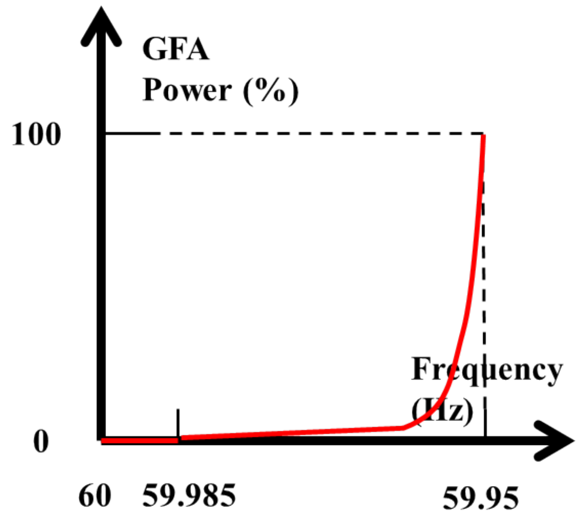
Power reduction vs frequency deviation –Extreme cases

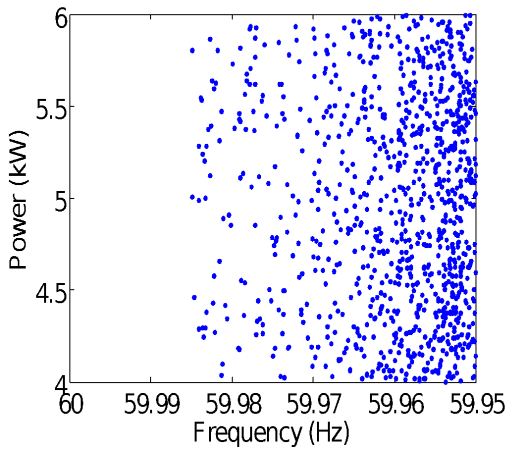
Unexpected behavior (cutoff frequencies are biased to the left)





Unexpected behavior (cutoff frequencies are biased to the right)





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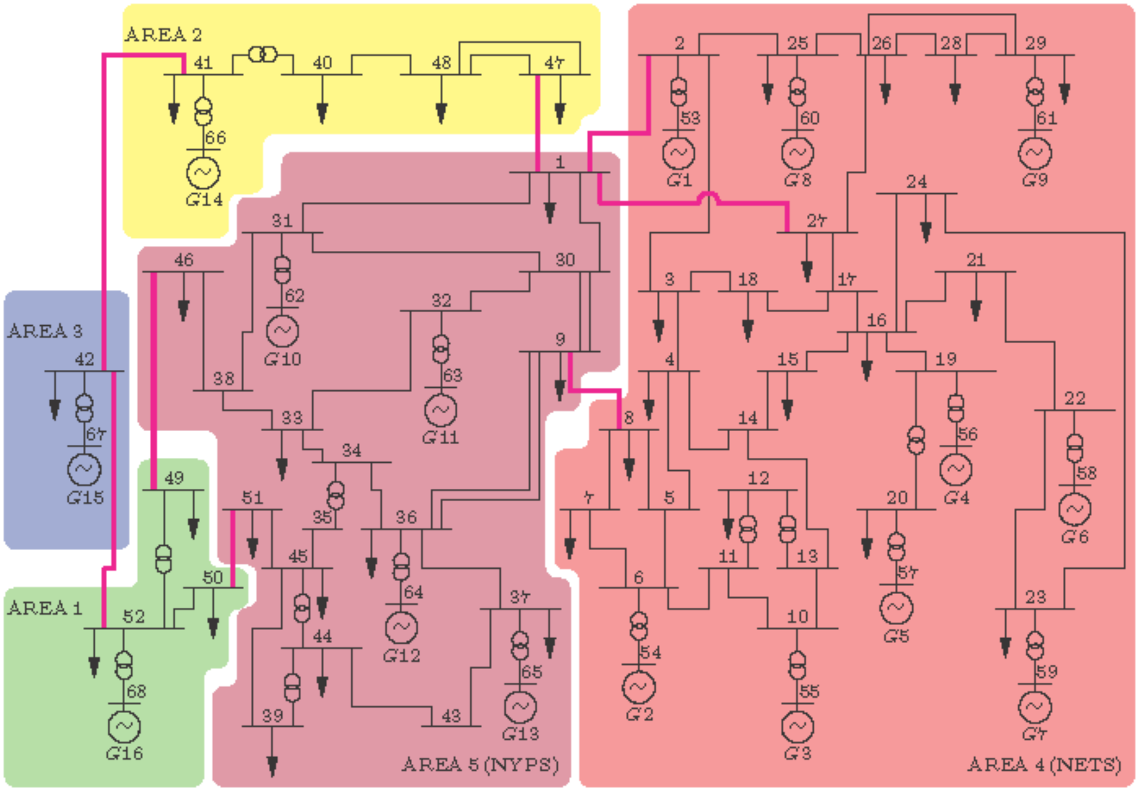
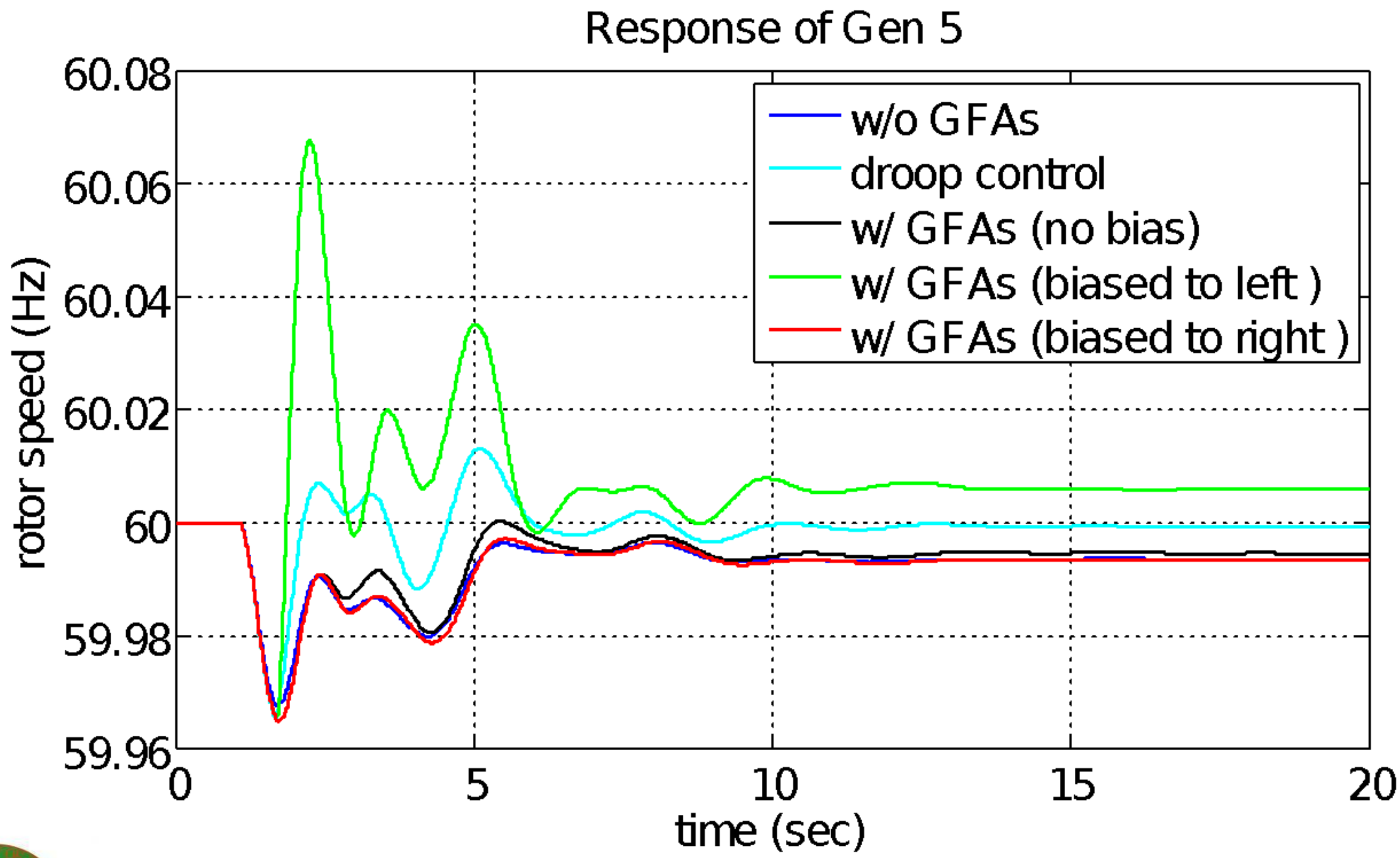
Test System

- IEEE 68-bus system
- GFA = Water heater
- 11% of total load in area 4 and area 5 (~1350 MW)
- Evenly distributed in area 4 and area 5
- Case One: Generator 1 was tripped
- Case Two: Generator 12 was tripped



Case One — Small Disturbance



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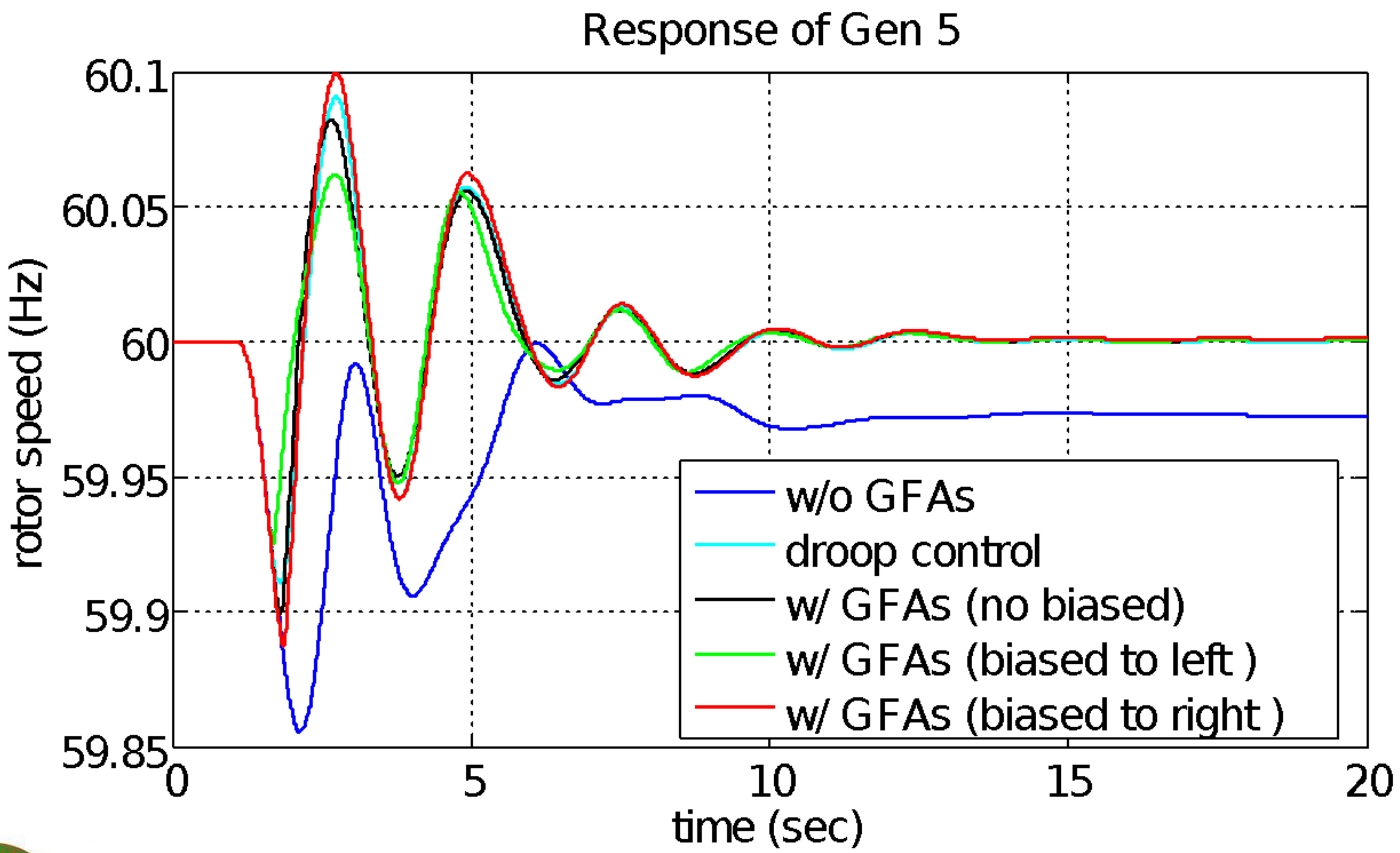
Case Two — Large Disturbance



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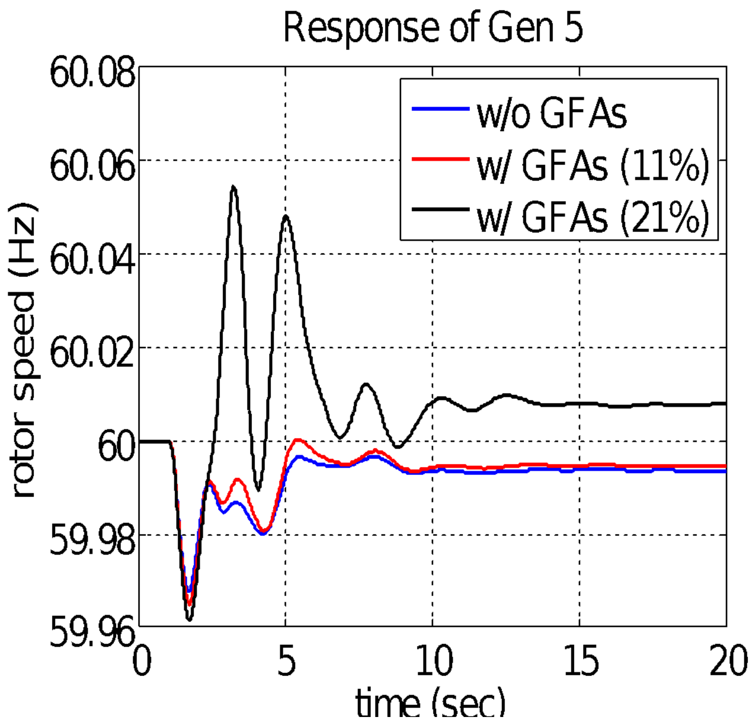
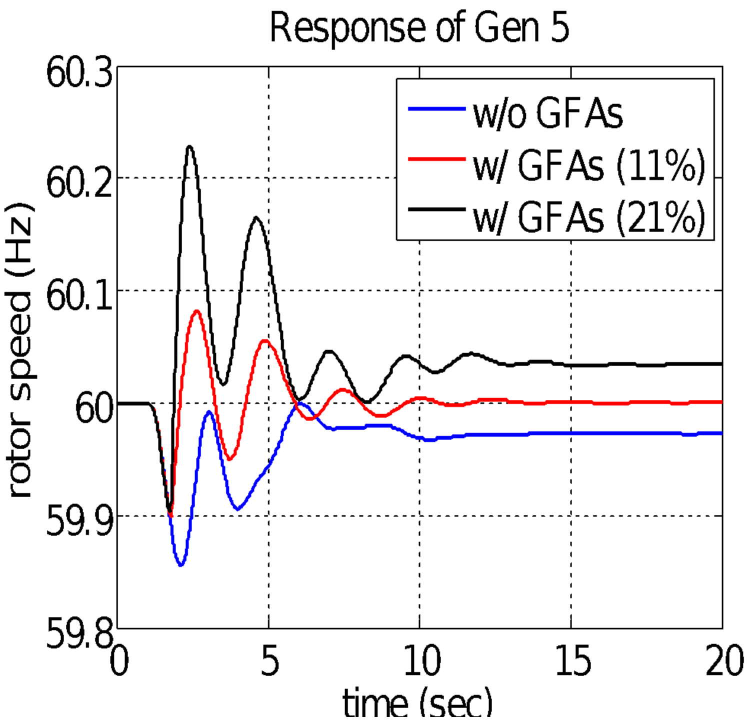
Higher penetration of GFAs

- 21% of total load in area 4 and area 5 (~2700 MW)

Small Disturbance



Large Disturbance



Conclusions –Task 3

- Derived boundaries to characterize system frequency performance under GFA control
- Droop-like desired response can not always be guaranteed due to random selection of cut-off frequencies
  - For small disturbances difference between desired response and actual response could be substantial
  - For large disturbances such differences are small
- Increasing penetration level leads to worse performance due to fixed cut-off frequency range

FY15 & beyond planned activities

- Hierarchical control strategy
  - Analyze interactions and integration of proposed control strategy with primary and secondary generator frequency controls and UFLS schemes
  - Study voltage “side effects” i.e. unintended consequences related to inherent modulation of reactive component of load while load is under primary frequency control
- Large-scale testing and validation studies
  - Improve representation of effect of distribution network and type of loads (e.g.; WECC composite load model or combine with feeder models in GridLAB-D)
  - Implement proposed hierarchical control strategy in integrated transmission & distribution environment (e.g. PowerWorld+ GridLAB-D)

FY15 & beyond planned activities

- GFA modeling and control design
  - Implement new GFA design in PowerWorld on the WECC system model
  - Perform extensive simulation studies to confirm FY14 findings regarding system response characterization
  - Enhance existing control design to deal with high penetration levels
- Preliminary field testing
  - Perform hardware-in-the-loop tests in PNNL lab homes for primary frequency control
- Outreach
  - Develop roadmap that outlines a strategy engaging various stakeholders (e.g. industry, utilities, WECC)