Next-Generation Frequency and Voltage Control using Inverter-Based Resources

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EPRI
ELECTRIC POWER RESEARCH INSTITUTE

NREL Workshop on Resilient Autonomous Energy Systems

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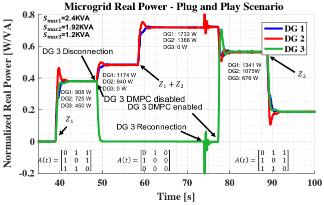
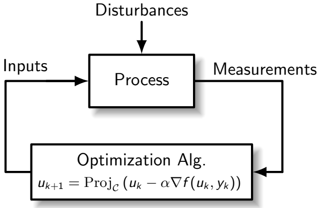
JWSP Group Research in Control and Power Systems

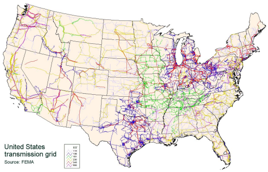
Control + Opt of Microgrids



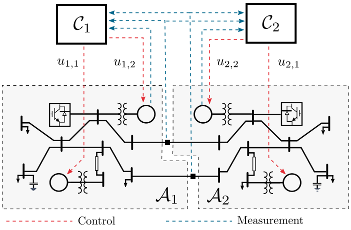
Feedback-Based Optimization



Robust Methods for Power Flow Analysis



Automatic Generation Ctrl.



Motivation

Selected Trends/Challenges in Grid Modernization:

1. reliability concerns from decreased inertia & new RES, DERs
2. inadequate legacy monitoring/control architectures (e.g., SCADA)

Required Advances for Next-Grid Control:

1. use of high-bandwidth **closed-loops** (e.g. 10+ samples/sec)
2. online coordination of heterogeneous **inverter-based resources** (IBRs)
3. **distributed hierarchical controls** for (i) integration of many devices, (ii) local situational awareness, (iii) low-latency localized response

- EPRI Whitepaper: "*Next-Generation Grid Monitoring and Control: Toward a Decentralized Hierarchical Control Paradigm*"

Enabling Fast Control via Inverter-Based Resources

Objectives and design constraints

Big Picture: fully leverage IBR capabilities for freq./volt. control

1. Design Objectives
   - **Fast** and **localized** compensation of disturbances
   - Hierarchical/decentralized architecture (min. delay, **scalability**)
   - State/control variable **constraint satisfaction**
2. Design Constraints
   - Premium on **simplicity** in design and implementation
   - Integrable with **legacy controls**
   - Uses **realistically available** model info.

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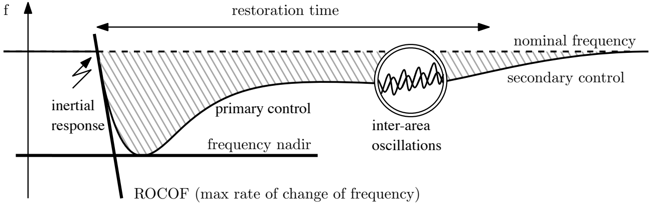
Outline of Talk

1. Frequency controller design
2. Voltage controller design
3. Joint frequency/voltage design

Review: Frequency Control in the Bulk Grid



Fundamentals of frequency control:

1. **Inertial** response: fast response of rotating machines

   Time scale: immediate

2. **Primary** control: turbine-governor control for *stabilization*

   Time scale: seconds. *Spatial scale*: local control, global response

3. **Automatic Generation Control (AGC)**: multi-area control which eliminates *generation-load mismatch* within each area

   Time scale: minutes. *Spatial scale*: area control, area response.

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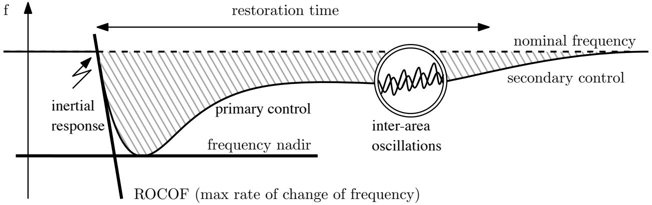

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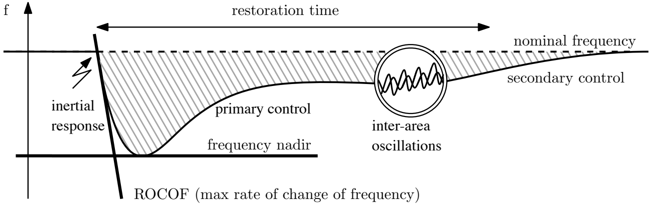

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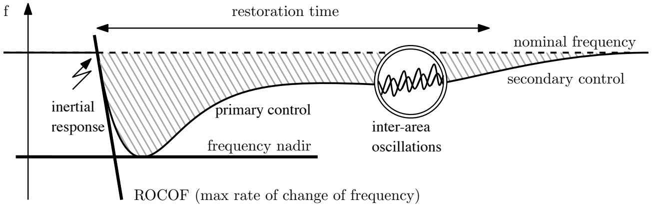

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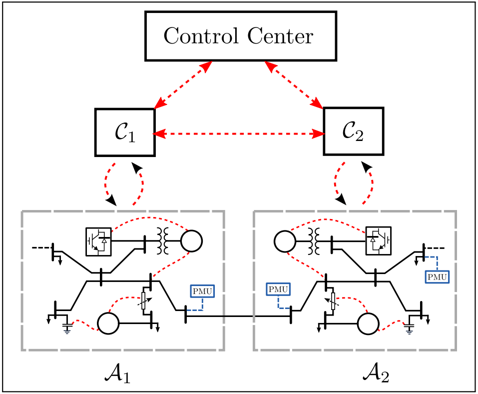
Overview of Proposed Frequency Controller



Bulk grid divided into small **local control areas** $\mathcal{A}_1, \ldots, \mathcal{A}_N$ (e.g., a few substations each)

Measurements and resources locally available within each LCA

1. **Stage 1:** LCA-decentralized controllers $\mathcal{C}_k$ redispatch local IBRs
2. **Stage 2:** Centralized coordination for severe contingencies

Conceptual goal: very **fast and localized** secondary-like response

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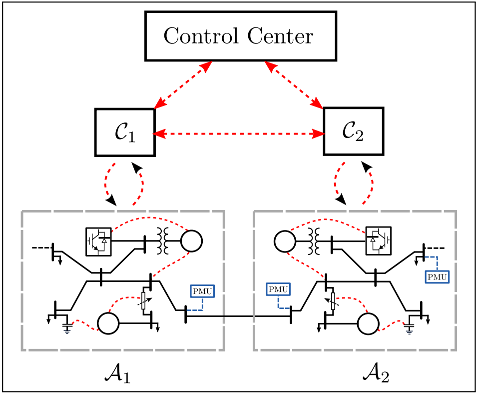

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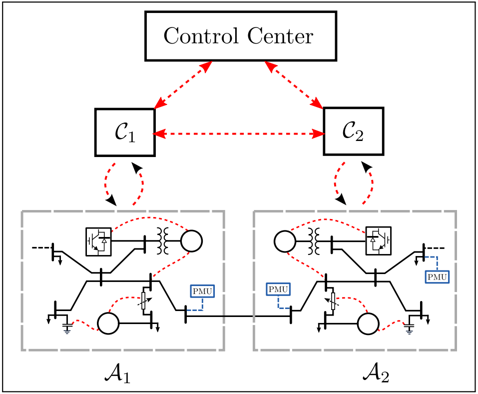

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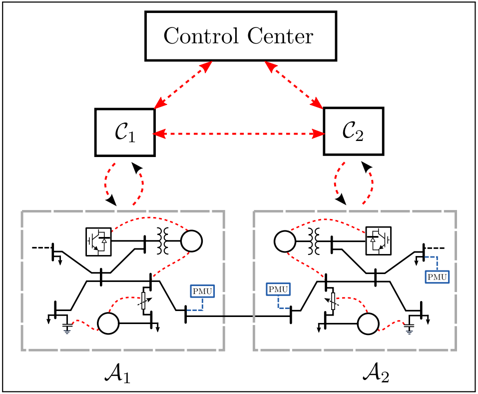

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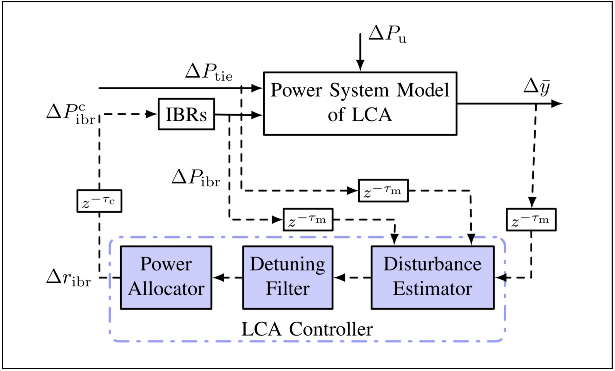
Philosophy: quickly estimate and compensate all local imbalance



IBRs: can have local f/P droop curve, but must **accept a provided set-point**

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2. **Detuning (if needed):** lower bandwidth to ensure robust stability
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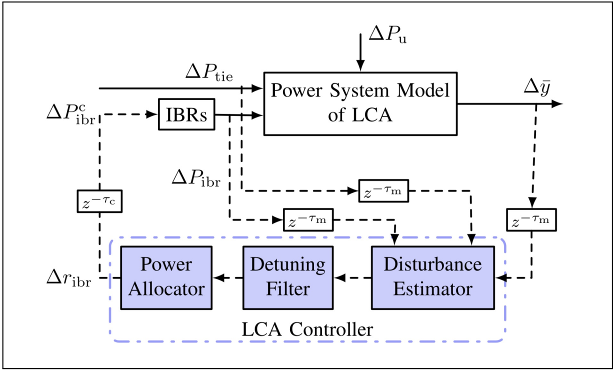

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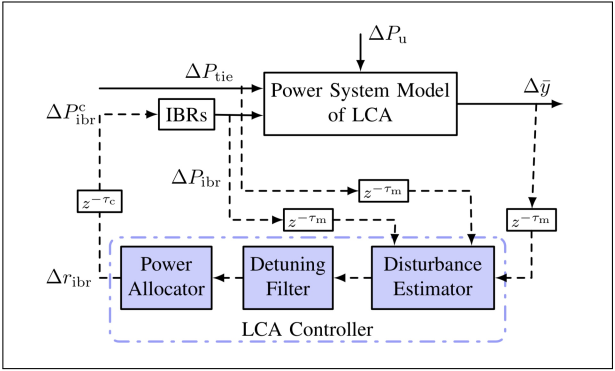

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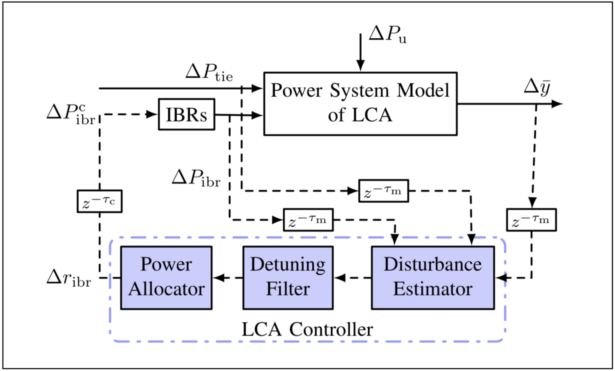

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Stage 1: Design of the Disturbance Estimator

An application of classical internal model control (IMC) . . .

1. A crude/**aggregate LCA model**, e.g.,

$$2H\Delta\dot{\omega} = -(D + \tfrac{1}{R_{\rm I}})\Delta\omega + \Delta P_{\rm m} - \Delta P_{\rm u} - \Delta P_{\rm inter} + \Delta P_{\rm ibr}^{\rm c}$$
$$T_{\rm R}\Delta\dot{P}_{\rm m} = -\Delta P_{\rm m} - R_{\rm g}^{-1}(\Delta\omega + T_{\rm R}F_{\rm H}\Delta\dot{\omega}),$$

   where $\Delta x = (\Delta\omega, \Delta P_{\rm m})$ and $\Delta P_{\rm u}$ = unknown gen/load mismatch

2. **Assume:** $\Delta\omega$ measured, $\Delta P_{\rm inter}$ measured (subj. to. delays)

3. Discretize LCA model & augment with **disturbance/delay models**

$$\Delta P_{\rm u}(k+1) = \Delta P_{\rm u}(k), \qquad \Delta\omega_{\rm m}(k) = \Delta\omega(k - \tau_{\rm d}), \ldots$$

4. Design **observer** (e.g., Kalman) to estimate $\Delta\hat{x}(k)$ **and $\Delta\hat{P}_{\rm u}(k)$**)

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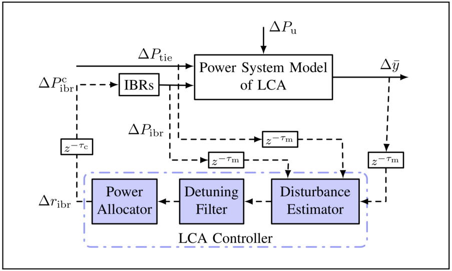

Detuning (optional):
low-pass filter

$$F(z) = \frac{1 - e^{-T/\tau}}{z - e^{-T/\tau}}$$

for lowering controller bandwidth

Power Allocator: Allocate disturbance estimate $\Delta \hat{P}_{\mathrm{u}}$ to compute IBR set-points P_{ik} within the ith LCA:

$$\begin{aligned} \underset{\varphi_i, P_{ik} \in [\underline{P}_{ik}, \overline{P}_{ik}]}{\text{minimize}} \quad & f_i(\{P_{ik}\}) + \lambda_i |\varphi_i| \\ \text{subject to} \quad & \sum\nolimits_{k \in I_i} (P_{ik} - P_{ik}^{\mathrm{dispatch}}) + \varphi_i = \Delta \widehat{P}_{\mathrm{u},i} \end{aligned}$$

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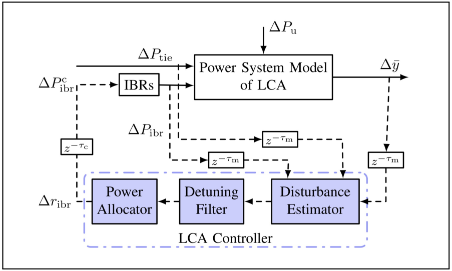

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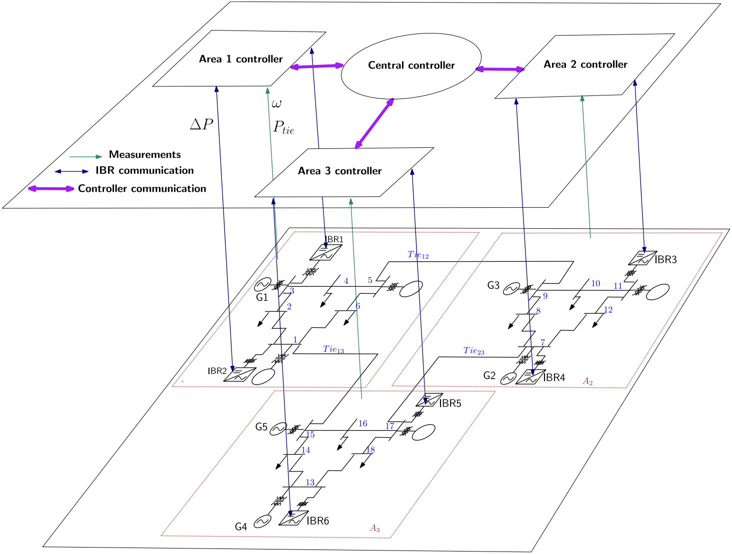
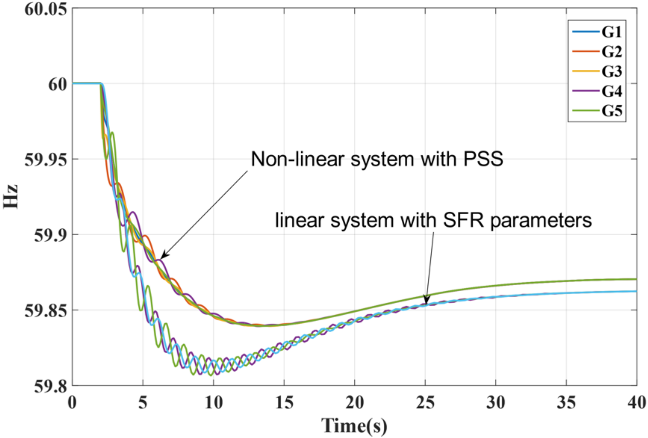
Case Study: Three-LCA System

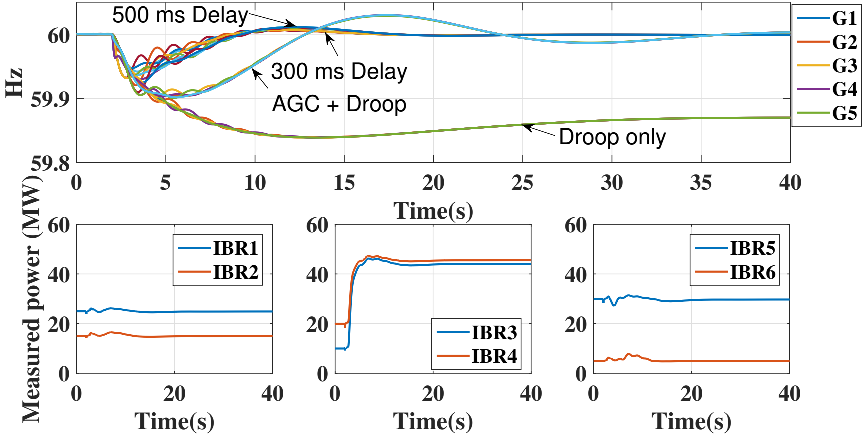


Simplified Model Response vs. True Nonlinear Model

- LCA model parameters set via simple inertia/droop gain aggregation and using largest turbine-gov time constant (**very crude!**)
- 63 MW load increase in Area 2



Scenario: 63 MW Disturbance, Area 2



Localized Response: IBRs in Area 2 ramp quickly; IBRs in Areas 1/3 don't *need* to react, so they don't.

Stage 2: Centralized Coordinator Design

What if local IBR capacity is **insufficient** to meet the disturbance?
Then IBRs in **electrically close** areas should respond.

- mismatch variable φ_i from Stage 1 will be **non-zero**
- total IBR adjustments a_i computed as

$$\begin{aligned} \underset{\{a_i\}_{i\in\mathcal{A}}}{\text{minimize}} \quad & \sum\nolimits_{i\in\mathcal{A}} q_i a_i^2 \\ \text{s.t.} \quad & 0 = \sum\nolimits_{i\in\mathcal{A}} (a_i - \varphi_i^*) \\ & 0 \leq a_i \cdot \text{sign}\Big(\sum\nolimits_{i\in\mathcal{A}} \varphi_i^*\Big), \qquad i \in \mathcal{A} \\ & a_i + \sum\nolimits_{j\in\mathcal{I}_i} P_{ij}^* \in [\text{lower}, \text{upper}], \quad i \in \mathcal{A}. \end{aligned}$$

Solution method matters! Centralized vs. privacy-preserving ADMM

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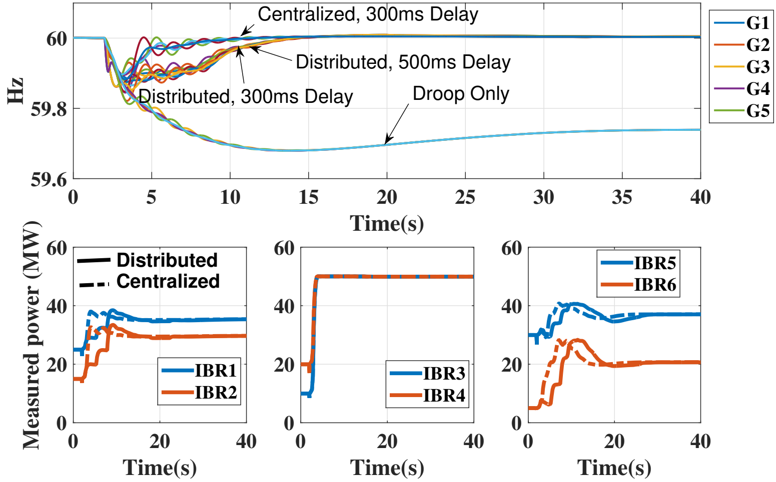
Scenario: 130MW Disturbance, Area 2



IBRs in Area 2 hit limits; Stage 2 forces Area 1/3 response.

Conclusions for Frequency Control

Summary:

- Two-stage design: local area control & global coordination
- Design enables **fast frequency control** via IBRs
- Response is **localized** to the contingency
- Inherent **robustness** against model imperfections

Ongoing:

- remove even the crude model requirement via **data-driven** control
- extend to incorporate **distribution**-integrated DERs

Paper: `https://www.control.utoronto.ca/~jwsimpson/`

1. IEEE TPWRS: "*Hierarchical Coordinated Fast Frequency Control using Inverter-Based Resources*"

Conclusions for Frequency Control

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- Two-stage design: local area control & global coordination
- Design enables **fast frequency control** via IBRs
- Response is **localized** to the contingency
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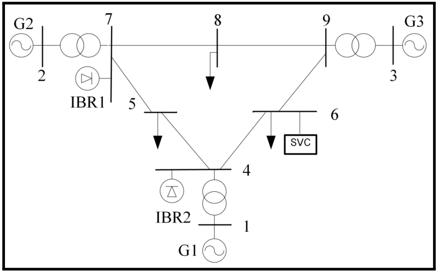
Overview of Proposed Voltage Controller (One-Area)



Control resources:

- SGs: $v_g^{\mathrm{ref}} \longrightarrow q_{\mathrm{g}}$
- SVCs: $v_s^{\mathrm{ref}} \longrightarrow q_{\mathrm{s}}$
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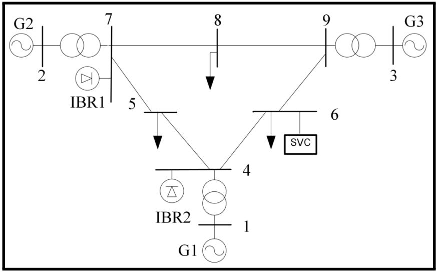

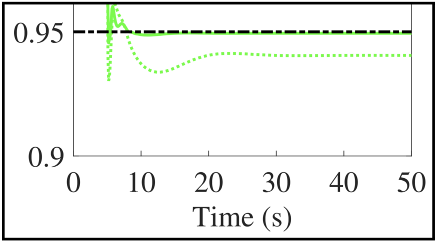

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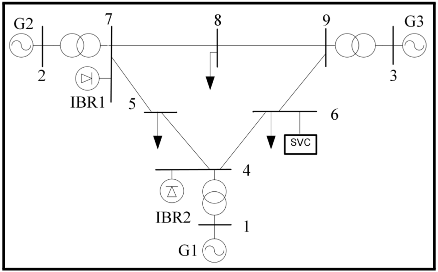

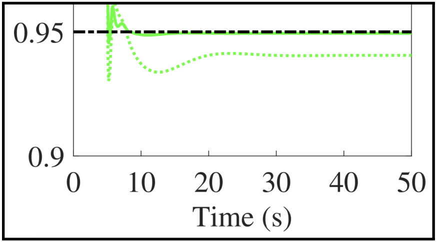

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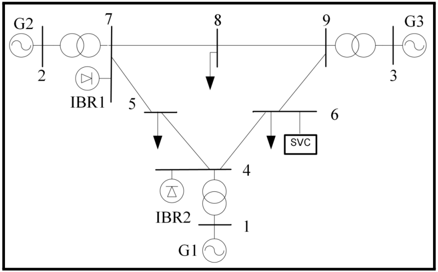

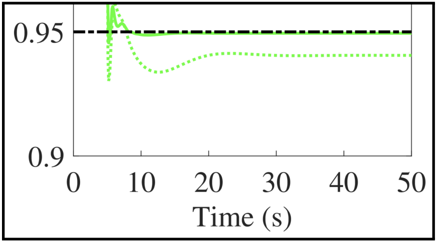

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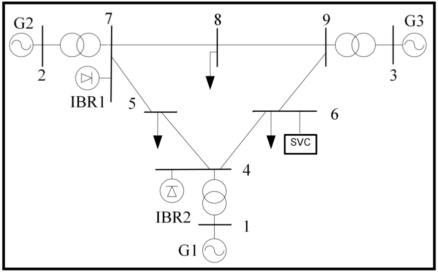
Model:
$$\dot{x} = f(x, u, w)$$
$$y = (v, q) = h(x, u, w)$$

$$\begin{aligned} \underset{u \in \{\text{Limits}\}}{\text{minimize}} \quad & f(q) \\ \text{subject to} \quad & \text{voltage limits} \\ & \text{power limits} \end{aligned}$$

Steady-State Optimization Problem (One-Area)

$$\begin{aligned} \underset{v_g^{\mathrm{ref}}, v_s^{\mathrm{ref}}, q_i^{\mathrm{ref}}}{\text{minimize}} \quad & \mathsf{Priority}(q_g, q_s, q_i) + \mathsf{PenaltyFcn}(q_g, q_s, v) := F(u, y) \\ \text{subject to} \quad & y = (q_g, q_s, v) = \pi(v_g^{\mathrm{ref}}, v_s^{\mathrm{ref}}, q_i^{\mathrm{ref}}, w) = \pi(u, w) \\ & u = (v_g^{\mathrm{ref}}, v_s^{\mathrm{ref}}, q_i^{\mathrm{ref}}) \in \mathcal{U} \end{aligned}$$



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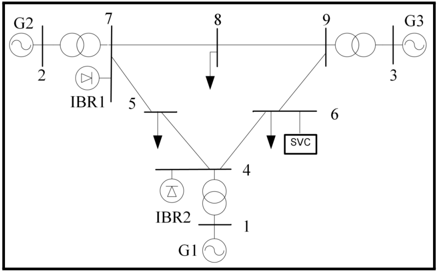

- vector y assumed to be **measurable** in real-time
- π = steady-state grid model from power flow eqns.
- **approximate sensitivities** $\Pi \approx \frac{\partial \pi}{\partial u}$ computable via load flow model

Feedback Implementation of Voltage Controller

- approximate gradient method steps can be evaluated using **real-time system measurements** leading to a **feedback controller**

$$u_{k+1} = \mathrm{Proj}_{\mathcal{U}}\Big\{u_k - \alpha\left(\nabla_u F(u_k, y_k) + \Pi^{\mathsf{T}}\nabla_y F(u_k, y_k)\right)\Big\}$$

- nonlinear controller implemented on a nonlinear dynamic transmission system; stability analysis is non-trivial

Theorem: Assume grid is nominally "stable" and "well-behaved'. If

$$u \mapsto \nabla_u F(u, \pi(u, w)) + \Pi^{\mathsf{T}}\nabla_y F(u, \pi(u, w))$$

is a **strongly monotone** operator, then CLS is stable for all sufficiently small controller gains $\alpha > 0$.

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Add-Ons and Extensions for Voltage Controller

The base controller is flexible and admits various modifications

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1. **Multi LCA Systems:** use one-area controller in each LCA
2. **Faster/Slower Unit Responses:** replace α with diagonal matrix $\alpha = \mathrm{blkdiag}(\alpha_{\mathrm{ibr}}, \alpha_{\mathrm{svc}}, \alpha_{\mathrm{sg}})$ and tune elements as desired
3. **Improved Recovery to Pre-Fault Operating Voltages**: integrate term proportional to $\|\Delta v_{\mathrm{sg}}\|_2^2$ into objective function
4. **Increased Transient Response:** integrate term proportional to $y_k - y_{k-1}$ into controller ("derivative" action)

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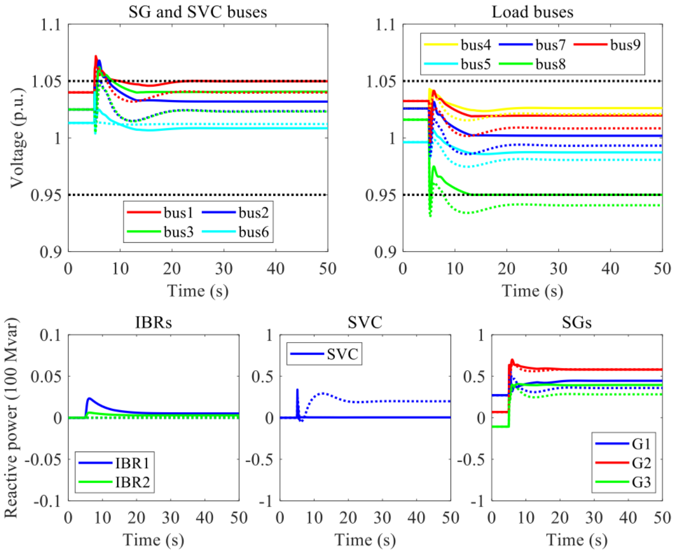
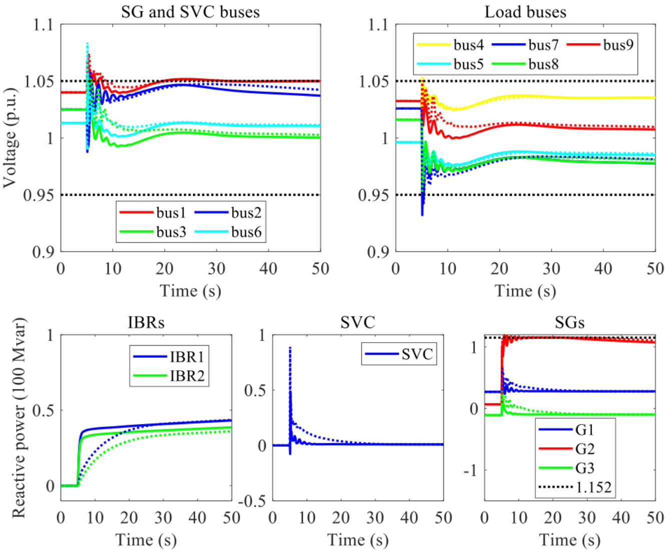
Scenario: 120 MVAR Disturbance (SG Priority)

solid: with proposed controller   dotted: without



Scenario: 180 MVAR Disturbance (G2/IBR Priority)

solid: with proposed controller dotted: **ignore**



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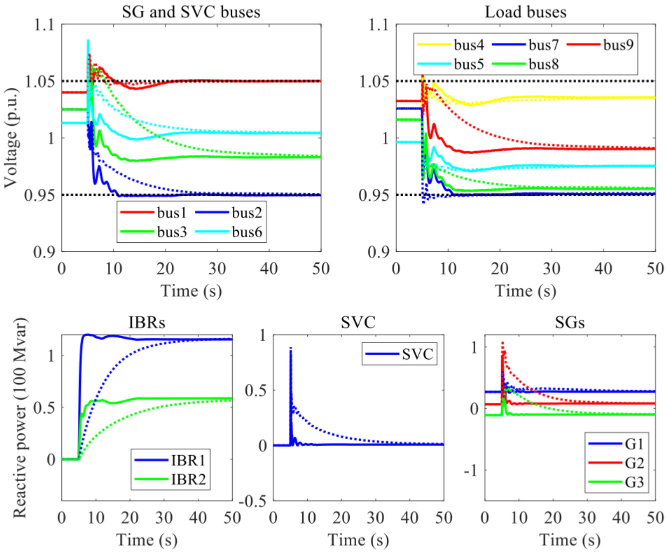

Conclusions for Voltage Control

Summary:

- Local area control based on local model/meas.
- Flexible design allows operator to set device priority
- Bus voltage and device output constraint satisfaction
- More scenarios: line trips, 3ϕ-fault, multi-areas, etc. ...

Ongoing:

- combine with online least-squares sensitivity estimation (model-free)
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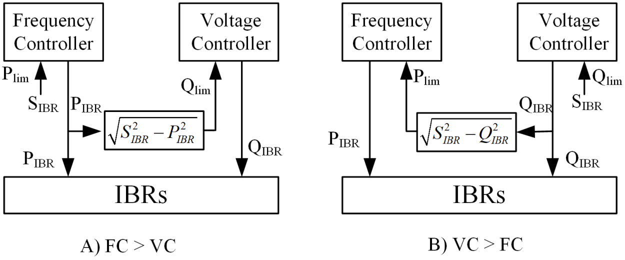
Integration of Freq. and Volt. Controllers

The two controllers can operate simultaneously.

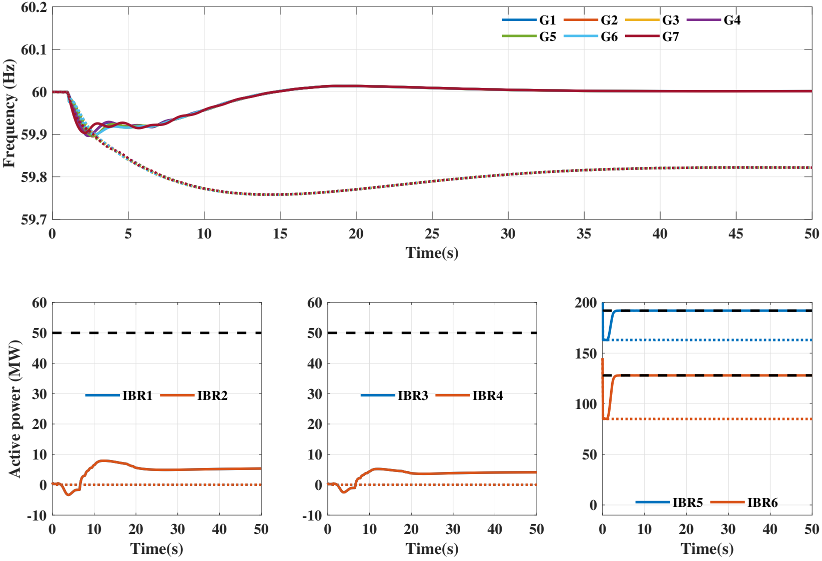
1. Allocate IBR capacity priority



2. Dynamic cross-couplings between controllers:
   - **voltage-sensitivity** of (e.g., impedance) loads
   - **PSS** and VC both operate through SG AVR systems

Scenario: 150MW/80MVAR Disturbance (FC Priority)

solid: with proposed controller dotted: without



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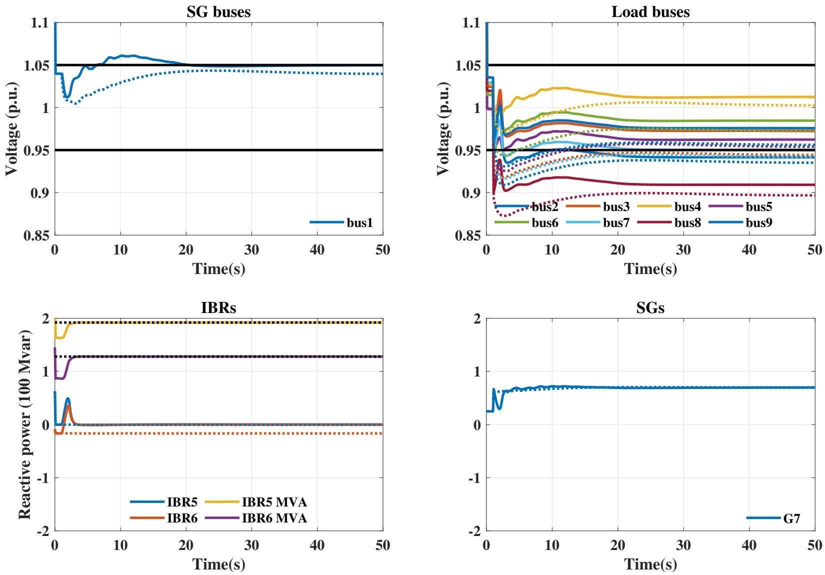
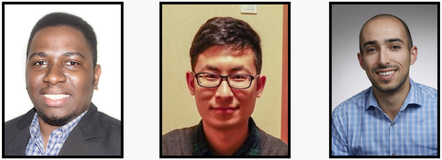


Collaborators

UWaterloo: Etinosa Ekomwenrenren (PhD), Zhiyuan Tang (PDF), JWSP



EPRI: Evangelos Farantatos, Mahendra Patel, Hossein Hooshyar, Aboutaleb Haddadi

Questions

The Edward S. Rogers Sr. Department
of Electrical & Computer Engineering
UNIVERSITY OF TORONTO

UNIVERSITY OF
WATERLOO

EPRI
ELECTRIC POWER
RESEARCH INSTITUTE

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Comparison with Traditional Frequency Control

Traditional frequency control:

1. **very fast** inertial response of machines limits ROCOF
2. primary layer (droop) provides **"fast" & global** stabilizing response
3. secondary layer (AGC) provides **slow & "localized"** response

Traditional frequency control + next-gen IBR controller:

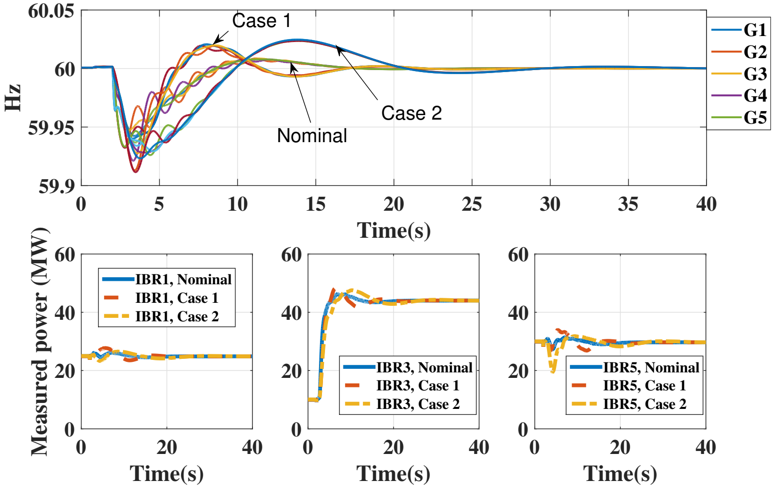
1. **very fast** inertial response of machines limits ROCOF
2. Stage 1 (local IBR redispatch) provides **fast & localized** response

   Ideally, **minimal activation** of SG turbine-govs

3. Stage 2 (global IBR redispatch) provides **fast & semi-local** response
4. AGC cleans up any remaining mismatch on minutes time-scale

Frequency Scenario: Robustness Test

- Introduce large (50%–100%) errors in parameters (H, T, R, ...) used for LCA disturbance estimator designs



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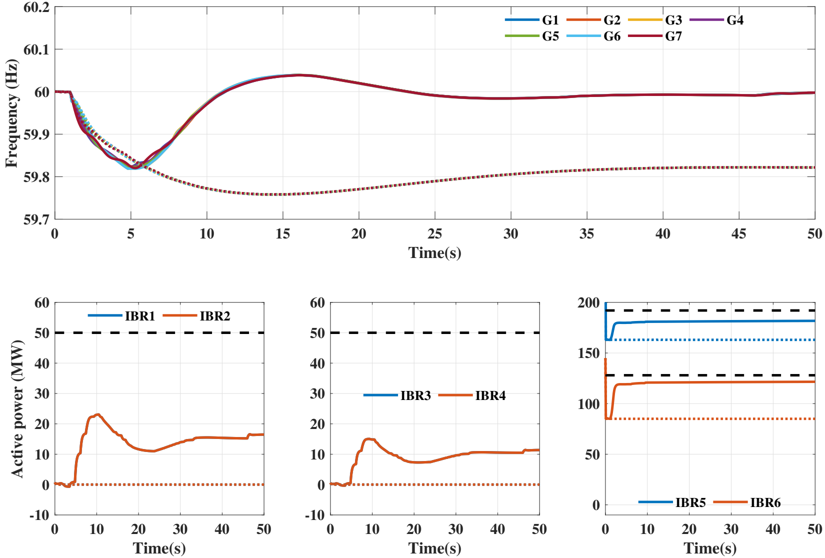

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