Hierarchical Power System Control using Fast Inverter-Based Resources

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UNIVERSITY OF TORONTO

PowerWeb Conference Keynote Talk
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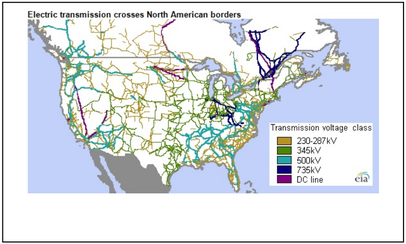
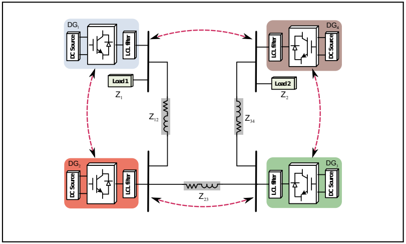
Research in Power System Control and Optimization

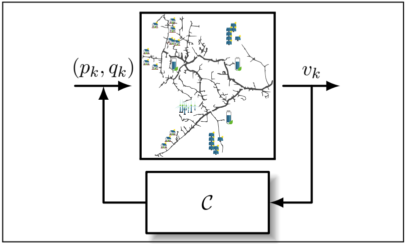
Power Flow Analysis & Algorithms



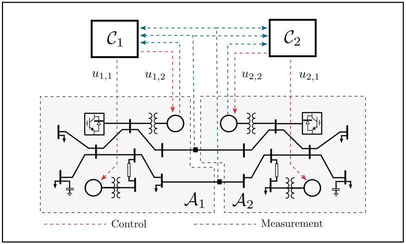
Microgrid Control & Optimization



Renewable Energy Integration



Next-Generation Hierarchical Control



Motivation for Advanced Grid Controls

Relevant Challenges:

1. RES integration $\Longrightarrow$ decreased inertia and control response
2. slow legacy monitoring/control architectures (e.g., SCADA)

(Some) Desirable Advances:

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

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

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Enabling Fast Control via Inverter-Based Resources

in other words, how do we make the modern grid more boring?

Big Picture: leverage fast actuators for fast control

1. Design Objectives
    - **Fast** and **localized** compensation of disturbances
    - Hierarchical/decentralized architecture (min. delay, **scalability**)
    - Maintain real-time **operating constraints**
2. Design Constraints
    - Premium on **simplicity** in design and implementation
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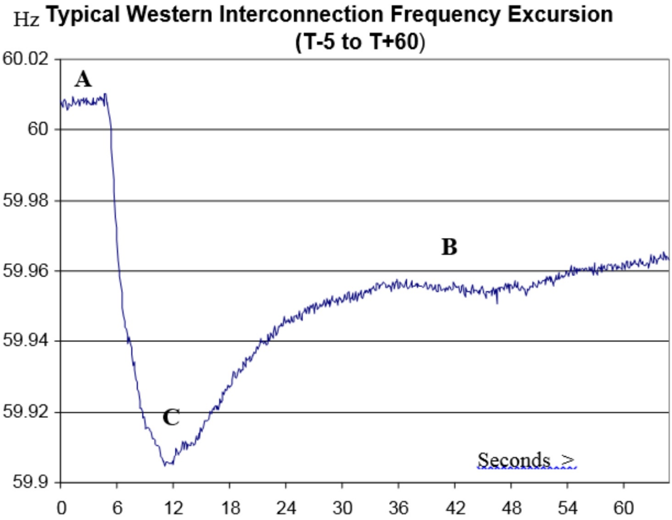
Outline of Talk

1. Fast Frequency Control via IBRs
2. Fast Voltage Control via IBRs (maybe)
3. Hierarchical Transmission/Distribution Coordination
4. Parting Thoughts

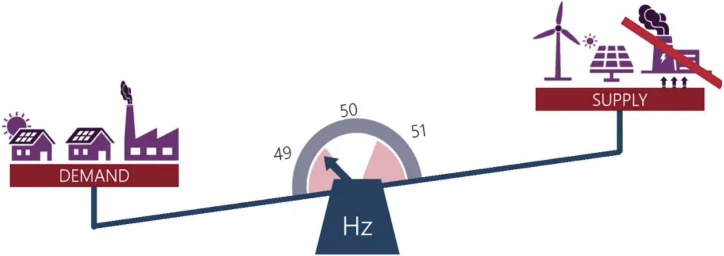
Primer on Traditional Frequency Control

Figure: NERC *Balancing and Frequency Control*



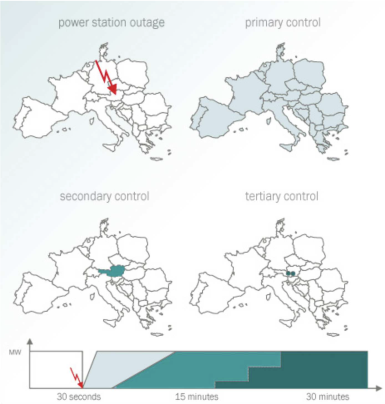
Frequency Control is Supply-Demand Balancing

Figure: AEMO

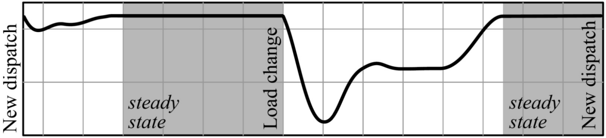


Stages of Power System Frequency Control

Figures: ENTSO-E, S. Dhople



- **Primary Control:** generators *everywhere* respond to help stabilize the frequency
- **Secondary Control: rebalances** the system so that every area achieves supply-demand balance
- **Tertiary Control:** Re-optimizes all generation minimize cost



Diagnosing The Patient

- Legacy frequency regulation is **slow**, because
  - (i) Turbine-governor systems on large generators are slow
  - (ii) The priority (correctly) is *robustness* not *performance*
  - (iii) High-inertia grids don't need fast rebalancing, so why bother
- Primary control essential, but provides limited localized response
- Regulation loop (LFC) is based on Cohn's frequency-biased net-interchange (ACE); this **ignores grid dynamics**

How should we re-think frequency control for low-inertia systems with fast actuators?

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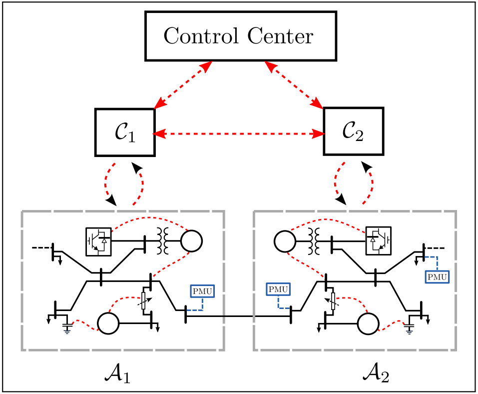
Overview of Proposed Frequency Controller



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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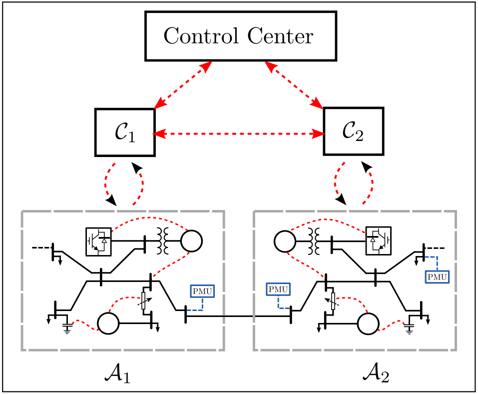

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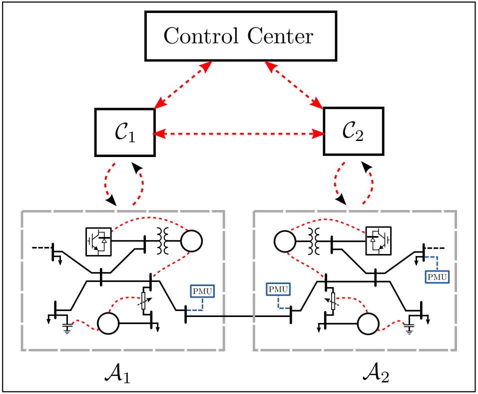

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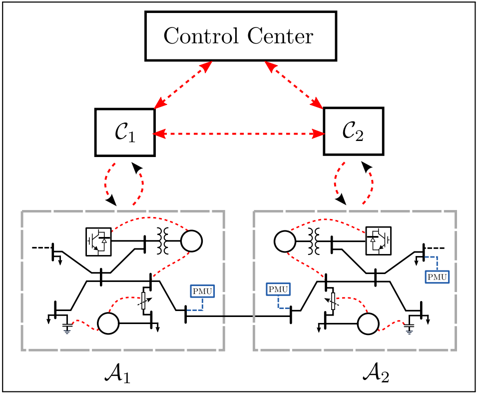

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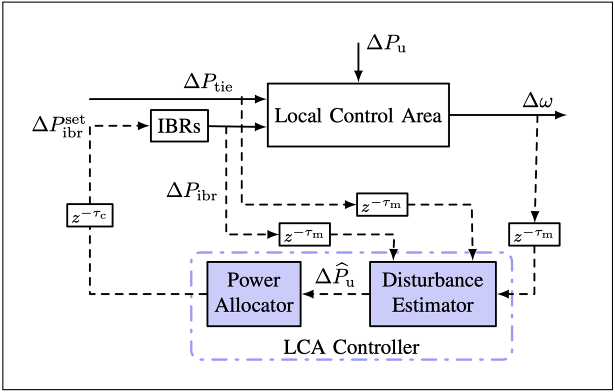
Stage 1: Local Control Area (LCA) Frequency Control

Philosophy: quickly estimate and compensate all local imbalance



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

1. **Disturbance Estimator:** real-time estimate of gen.-load mismatch
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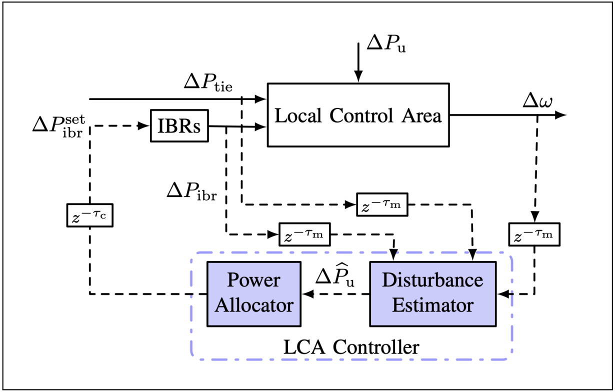

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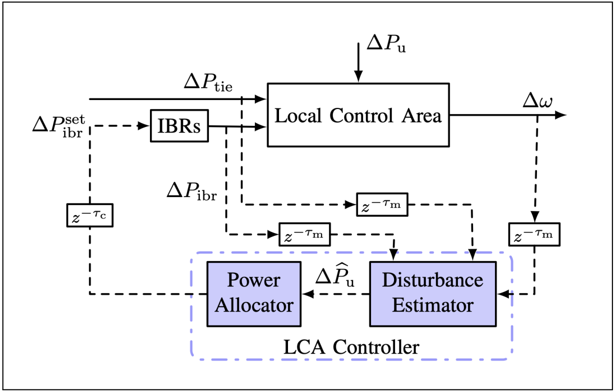

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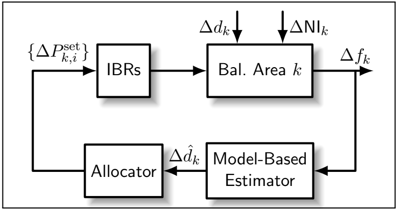
Model-Based Fast Frequency Control

E. Ekomwenrenren et al., "Hierarchical Coordinated Fast Frequency Control . . . ," in IEEE TPWRS, 2021.



- IBRs have local droop curve

$$T_{k,i}\Delta \dot{P}_{k,i} = -\Delta P_{k,i} - \frac{\Delta f_{k,i}}{R_{k,i}} + \Delta P_{k,i}^{\text{set}}$$

- Inverter controls ensure $T_{k,i}$ is small (e.g., 200ms)

- **Identify** a simple dynamic model for each area + IBR dynamics

$$\Delta \dot{x}_k = A_k \Delta x_k + B_k(\Delta P_k^{\text{set}} - \Delta d_k + \Delta \text{NI}_k), \qquad \Delta f_k = C \Delta x_k$$

- Fictitious disturbance model $\Delta \dot{d}_k = 0 \quad \Longrightarrow \quad$ Extended-state observer

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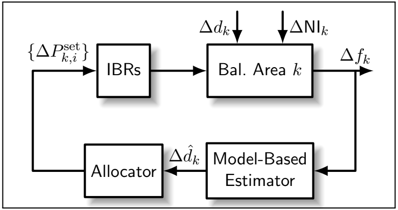

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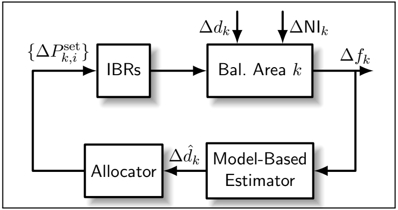

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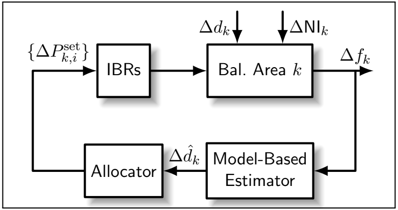

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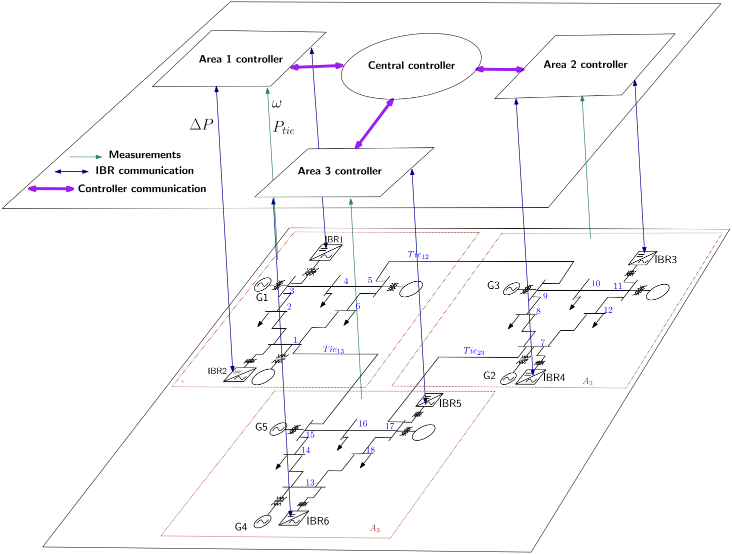
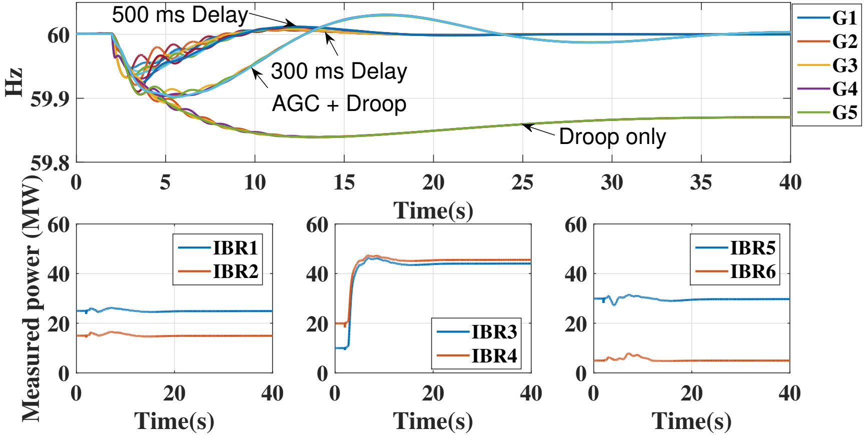
Case Study: Three-Area System

About 230MW per area



Scenario: 63 MW Disturbance, Area 2

- Design based on **lumped** generator + governor model

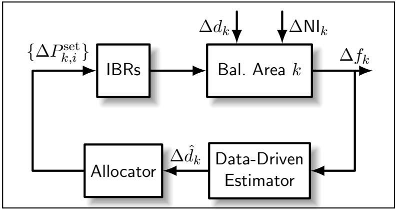


Localized Response in Area 2

Data-Driven Fast Frequency Control

E. Ekomwenrenren et al., "Data-Driven Fast Frequency Control . . . ," in IEEE TPWRS, 2024 (Hopefully!)

The *model-based* estimator can be replaced with a direct **data-driven estimator**



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2. **Offline:** construct Hankel matrices of depth L using data

$$\mathscr{H}_L(\Delta v_{\mathrm{d}}) = \begin{bmatrix} \Delta v_{\mathrm{d}}(1) & \cdots & \Delta v_{\mathrm{d}}(T-L+1) \\ \vdots & \ddots & \vdots \\ \Delta v_{\mathrm{d}}(L) & \cdots & \Delta v_{\mathrm{d}}(T) \end{bmatrix}, \quad \mathscr{H}_L(\Delta f_{\mathrm{d}}) \text{ similar}$$

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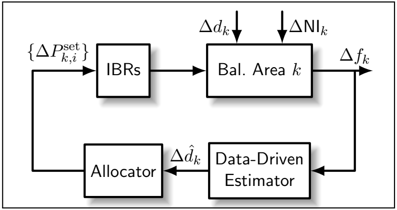

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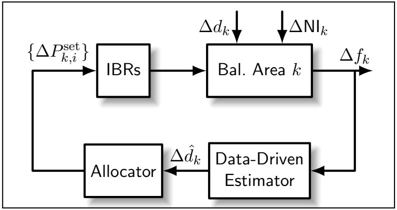
$$\mathscr{H}_L(\Delta v_{\mathrm{d}}) = \begin{bmatrix} \Delta v_{\mathrm{d}}(1) & \cdots & \Delta v_{\mathrm{d}}(T-L+1) \\ \vdots & \ddots & \vdots \\ \Delta v_{\mathrm{d}}(L) & \cdots & \Delta v_{\mathrm{d}}(T) \end{bmatrix}, \quad \mathscr{H}_L(\Delta f_{\mathrm{d}}) \text{ similar}$$

Data-Driven Fast Frequency Control

E. Ekomwenrenren et al., "Data-Driven Fast Frequency Control . . . ," in IEEE TPWRS, 2024 (Hopefully!)

The *model-based* estimator can be replaced with a direct **data-driven estimator**



① **Offline:** excite the area with IBRs and collect T samples of I/O data:

$$\begin{aligned}\Delta v_{\mathrm{d}} &= (\Delta v_{\mathrm{d}}(1), \Delta v_{\mathrm{d}}(2), \ldots, \Delta v_{\mathrm{d}}(T)), \qquad v = \Delta P^{\mathrm{set}} + \Delta \mathrm{NI} \\ \Delta f_{\mathrm{d}} &= (\Delta f_{\mathrm{d}}(1), \Delta f_{\mathrm{d}}(2), \ldots, \Delta f_{\mathrm{d}}(T))\end{aligned}$$

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Data-Driven Fast Frequency Control

E. Ekomwenrenren et al., "Data-Driven Fast Frequency Control . . . ," in IEEE TPWRS, 2023.

3. **Online:** perform **data-driven simulation** to predict $\Delta f(t)$:

$$\underbrace{\begin{bmatrix}\mathscr{H}_{T_\mathrm{p}+1}(\Delta v_\mathrm{d})\\ \mathscr{H}_{T_\mathrm{p}+1}(\Delta y_\mathrm{d})\end{bmatrix}}_{\text{Hankel}} g \triangleq \begin{bmatrix}V_\mathrm{p}\\ V\\ F_\mathrm{p}\\ F\end{bmatrix} g = \begin{bmatrix}\Delta v_\mathrm{p} + \Delta\hat{d}_p\\ \mathbf{0}\\ \Delta\hat{f}_\mathrm{p}\\ \Delta\hat{f}(t)\end{bmatrix} \implies \Delta\hat{f}(t) = F\begin{bmatrix}V_\mathrm{p}\\ V\\ F_\mathrm{p}\end{bmatrix}^{\dagger}\begin{bmatrix}\Delta v_\mathrm{p} + \hat{d}_p\\ \mathbf{0}\\ \Delta\hat{f}_\mathrm{p}\end{bmatrix}$$

4. **Online:** linear update of estimate $\Delta\hat{d}(t)$ using prediction error:

$$\Delta\hat{d}(t) = \Delta\hat{d}(t-1) - \epsilon L(\Delta\hat{f}(t) - \Delta f(t)), \qquad \epsilon \in (0,1),\ L = G(1)^{-1}$$

$$G(1) = \text{DC Gain} \qquad \text{(computable directly from the above data)}$$

This is a data-driven implementation of a disturbance estimator.
Optimization-based receding-horizon estimator also developed.

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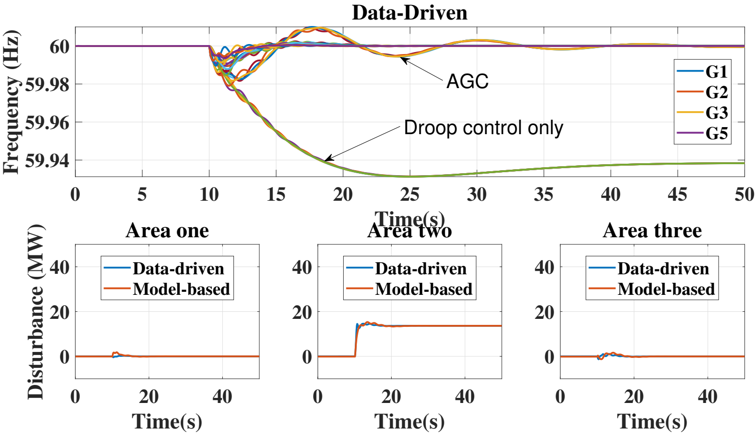
Scenario: 60 MW Disturbance, Area 2

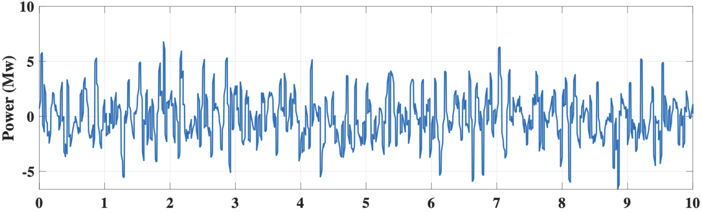


- Imbalance is **quickly localized and rejected** by controller
- Fast emergency control to enhance grid reliability

Comments on Data for Data-Driven Collection

- Probing power injection = harmonic + noise

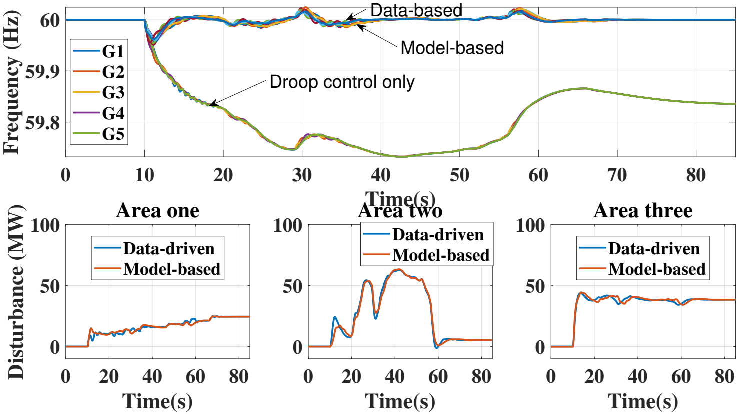
$$\Delta P_{\mathrm{ibr}}(t) = \sin(12\pi t) + w(t)$$



- 10 samples/s for 10 seconds = **100 total data points**
- SVD truncation eliminates irrelevant dynamic modes
- Classical SysID (or equivalent) completely sufficient . . .

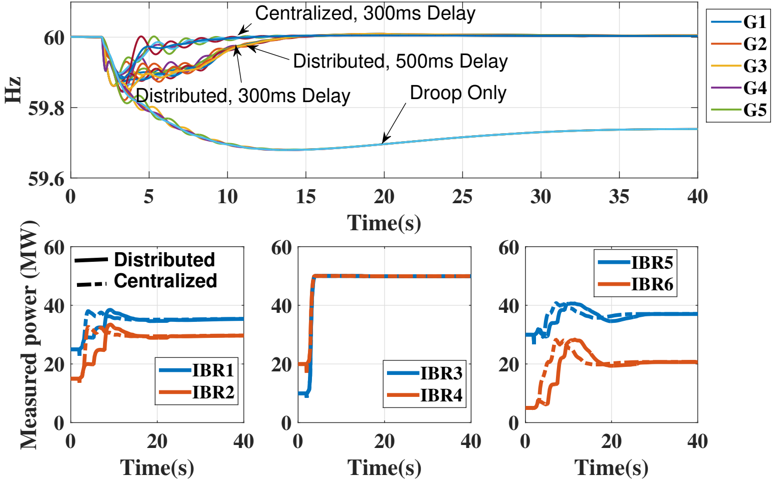
Scenario: Compensating for Renewables

- Uncontrolled wind and solar ($\approx$ 300 MW) integrated into system
- Major unexpected decreases in RES across grid ($\approx$ 125MW total peak)

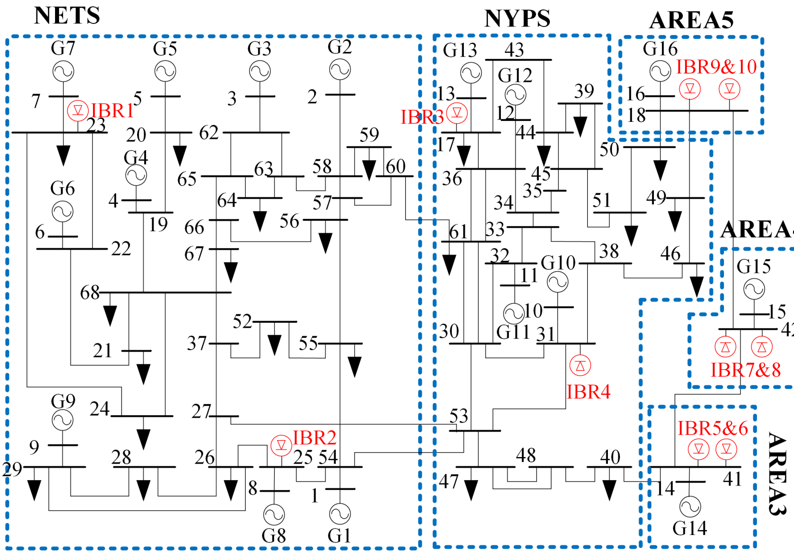


Scenario: 130MW Disturbance, Area 2

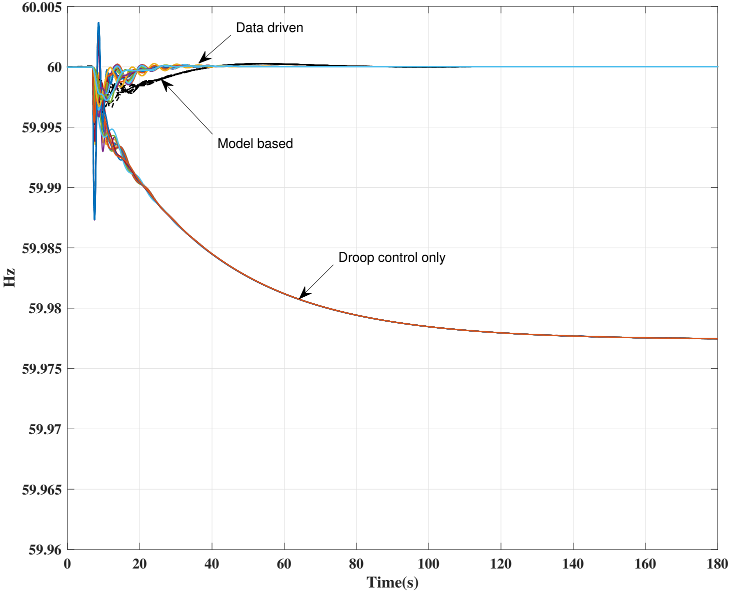
- Central controller kicks in when Area 2 runs out of supply



Five-Area 68 Bus Test System

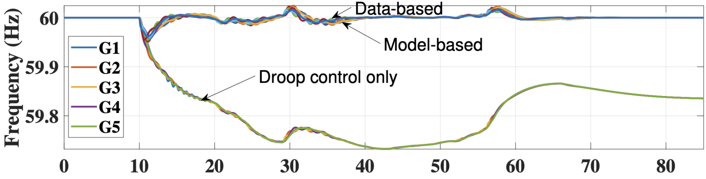


Scenario: 300MW Load Change in NYPS Area



Key Insights

Summary: You can significantly enhance frequency control **if** you have fast dispatchable reserves **and** a *bit* of advanced control.

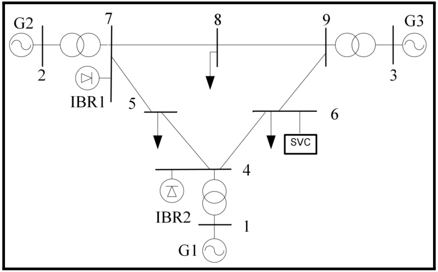


- Can provide contingency **resilience** for low-inertia systems
- As always, beware of communication delays

Challenge: where are these reserves going to come from?

Overview of Proposed Voltage Controller (One-Area)

Z. Tang *et al. Measurement-Based Fast Coordinated Voltage Control* . . . in IEEE TPWRS, 2021.



Control resources:

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

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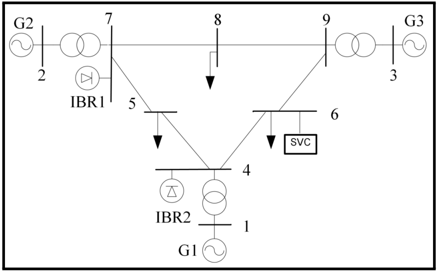

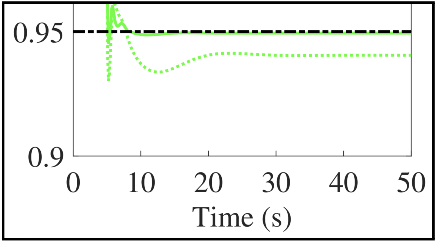

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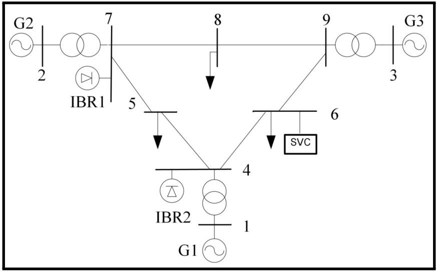

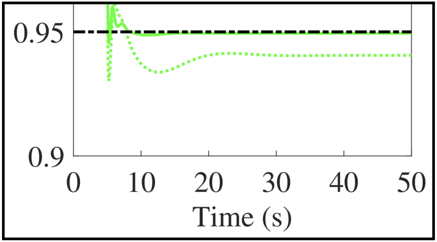

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- $q =$ vector of power outputs

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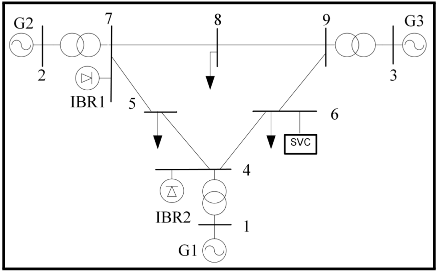

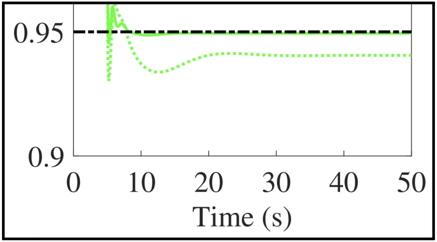

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Model:

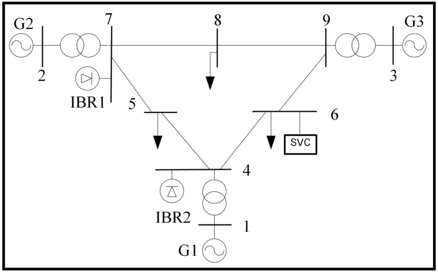
$$\begin{aligned} \dot{x} &= f(x, u, w) \\ y = (v, q) &= h(x, u, w) \end{aligned}$$

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

Steady-State Optimization Problem (One-Area)

Z. Tang *et al. Measurement-Based Fast Coordinated Voltage Control* ... in IEEE TPWRS, 2021.

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



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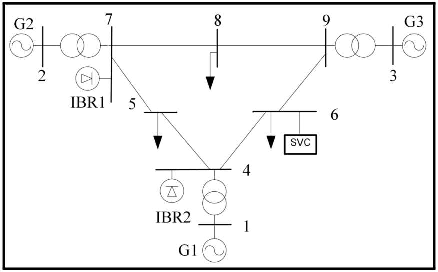
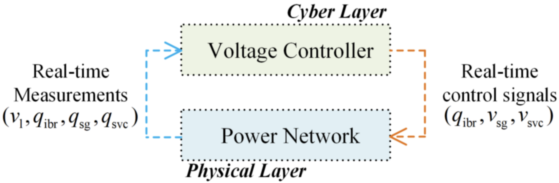


- vector y assumed to be **measurable** in real-time
- π = steady-state grid model
- **approximate sensitivities** $\Pi \approx \frac{\partial \pi}{\partial u}$ via load flow model

Feedback Implementation of Voltage Controller

Z. Tang *et al. Measurement-Based Fast Coordinated Voltage Control* . . . in IEEE TPWRS, 2021.

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



- Advantages:
  - (i) Optimizes system resources and maintains constraints
  - (ii) Simple to implement and tune
  - (iii) Integrates with legacy voltage control systems
  - (iv) Comes with stability guarantees

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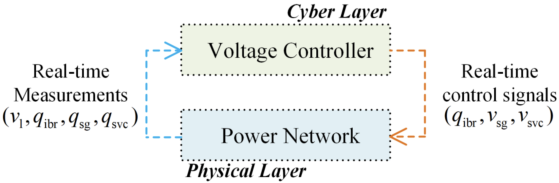

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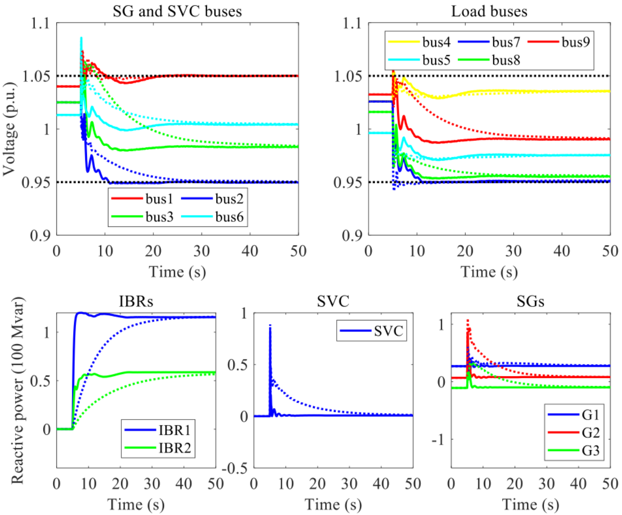
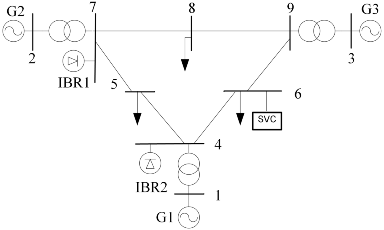
Scenario: IBRs Providing Reactive Power Support

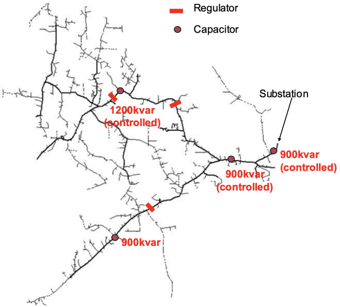
solid: with proposed controller dotted: **ignore**



The Need for Transmission-Distribution Coordination

- Only very large storage and RES facilities are transmission-connected
- Most RES/DERs are connected at the **distribution level**





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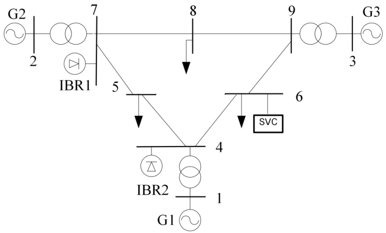
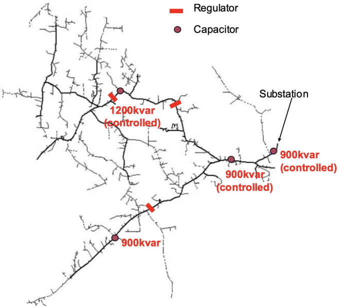




Can we **hierarchically coordinate** resources in the distribution system to **collectively respond** like a fast transmission-connected resource?

Multi-Area Hierarchical DN Control: Objectives

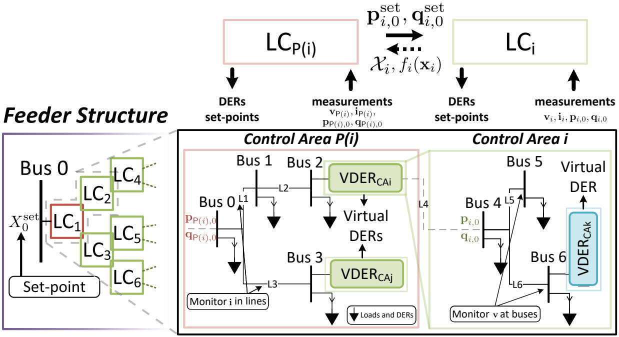
(i) Respond **fast** to power change requests by TSO

(ii) **Area-based** (e.g., aggregator) control using only local measurements

(iii) Maintain voltage and current constraints in DN

(iv) Grid and DER models kept **private** to each area controller

(v) Design must be **agnostic** to specifics of DERs



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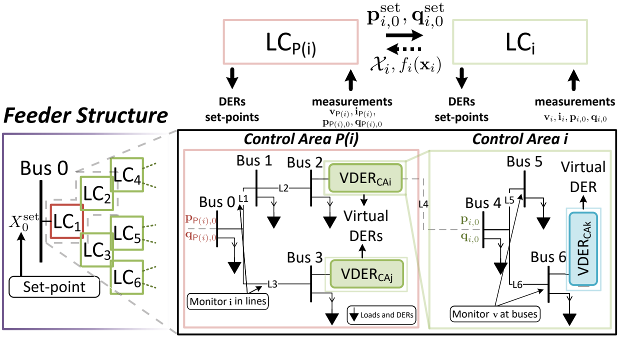

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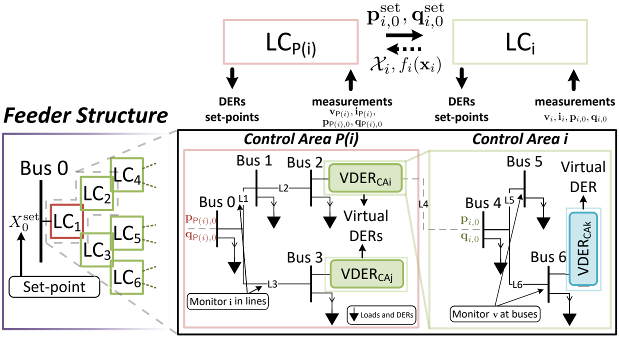

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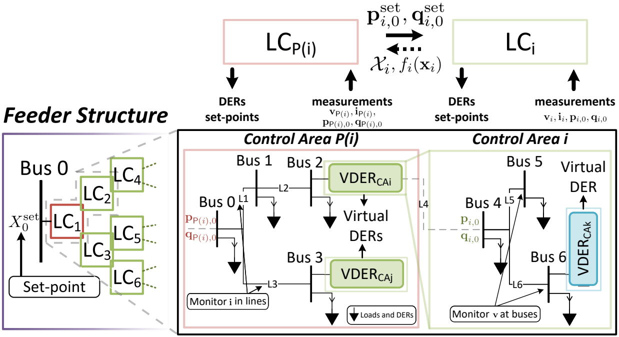

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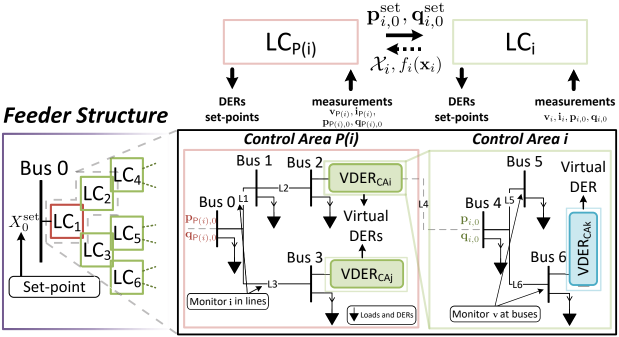

Area Controller Design

Farhat *et al. A Multi-Area Architecture for Real-Time Feedback-Optimization* . . . , IEEE TSG, 2024 (Hopefully!)

Control Area i Design:

- $x_j = (\mathrm{p}_j, \mathrm{q}_j)$ are DER **set-points**
- *Child areas* $\mathsf{C}(i)$ abstracted as **virtual DERs**
- $f_{ij}(x_j)$ = control cost of DER j
- $\mathbf{p}_{i,0}, \mathbf{q}_{i,0}$ = power export to the *Parent Area* $\mathsf{P}(i)$

$$\begin{aligned}
\underset{\mathbf{x}_i \in \boldsymbol{\mathcal{X}}_i}{\text{minimize}} \quad & \sum_{j \in \mathcal{D}_i} f_{ij}(x_j) \\
\text{subject to} \quad & \mathbb{1}^\mathsf{T} \mathbf{p}_{i,0}(\mathbf{x}_i) = \mathrm{p}_{i,0}^{\text{set}}(\mathbf{x}_{\mathsf{P}(i)}) \\
& \mathbb{1}^\mathsf{T} \mathbf{q}_{i,0}(\mathbf{x}_i) = \mathrm{q}_{i,0}^{\text{set}}(\mathbf{x}_{\mathsf{P}(i)}) \\
& \underline{\mathbf{v}}_i \leq \mathbf{v}_i(\mathbf{x}_i) \leq \overline{\mathbf{v}}_i \\
& \mathbf{i}_i(\mathbf{x}_i) \leq \overline{\mathbf{i}}_i
\end{aligned}$$

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Farhat *et al. A Multi-Area Architecture for Real-Time Feedback-Optimization* . . . , IEEE TSG, 2024 (Hopefully!)

Control Area i Design:

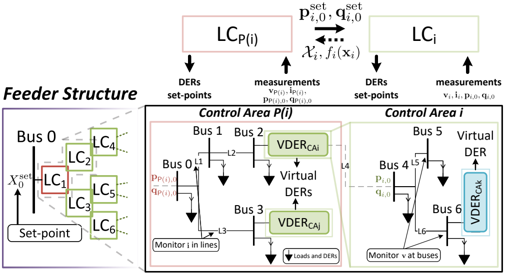
- $x_j = (\mathrm{p}_j, \mathrm{q}_j)$ are DER **set-points**
- *Child areas* $\mathsf{C}(i)$ abstracted as **virtual DERs**
- $f_{ij}(x_j)$ = control cost of DER j
- $\mathbf{p}_{i,0}, \mathbf{q}_{i,0}$ = power export to the *Parent Area* $\mathsf{P}(i)$

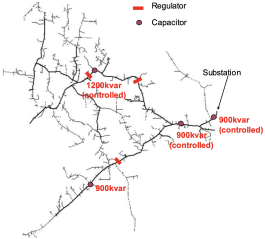
$$\begin{aligned} \underset{\mathbf{x}_i \in \boldsymbol{\mathcal{X}}_i}{\text{minimize}} \quad & \sum_{j \in \mathcal{D}_i} f_{ij}(x_j) \\ \text{subject to} \quad & \mathbb{1}^{\mathsf{T}} \mathbf{p}_{i,0}(\mathbf{x}_i) = \mathrm{p}^{\mathrm{set}}_{i,0}(\mathbf{x}_{\mathsf{P}(i)}) \\ & \mathbb{1}^{\mathsf{T}} \mathbf{q}_{i,0}(\mathbf{x}_i) = \mathrm{q}^{\mathrm{set}}_{i,0}(\mathbf{x}_{\mathsf{P}(i)}) \\ & \underline{\mathbf{v}}_i \leq \mathbf{v}_i(\mathbf{x}_i) \leq \overline{\mathbf{v}}_i \\ & \mathbf{i}_i(\mathbf{x}_i) \leq \bar{\mathbf{i}}_i \end{aligned}$$

```
Algorithm 1: LC Controller for $i$th CA
    At each sampling time
    [Step 1]: Receive set-points from LC of parent area $\mathsf{P}(i)$
        $\mathrm{p}^{\mathrm{set}}_{i,0}(\mathbf{x}_{\mathsf{P}(i)}) = T^{\mathrm{p}}_i \mathbf{x}_{\mathsf{P}(i)}, \quad \mathrm{q}^{\mathrm{set}}_{i,0}(\mathbf{x}_{\mathsf{P}(i)}) = T^{\mathrm{q}}_i \mathbf{x}_{\mathsf{P}(i)}$
    [Step 2]: Collect local measurements $\mathbf{p}_{i,0}, \mathbf{q}_{i,0}, \mathbf{v}_i, \mathbf{i}_i, \underline{\mathbf{x}}_i, \overline{\mathbf{x}}_i$
    [Step 3]: LC performs the updates
        $\lambda_i^+ = \mathcal{P}_{\geq 0}\left(\lambda_i + \alpha_{\lambda_i}\left(\mathbb{1}^{\mathsf{T}}\mathbf{p}_{i,0} - \mathrm{p}^{\mathrm{set}}_{i,0} - E_{i_p} - r_{\lambda_i}\lambda_i\right)\right)$
        $\mu_i^+ = \mathcal{P}_{\geq 0}\left(\mu_i + \alpha_{\mu_i}\left(\mathrm{p}^{\mathrm{set}}_{i,0} - \mathbb{1}^{\mathsf{T}}\mathbf{p}_{i,0} - E_{i_p} - r_{\mu_i}\mu_i\right)\right)$
        $\eta_i^+ = \mathcal{P}_{\geq 0}\left(\eta_i + \alpha_{\eta_i}\left(\mathbb{1}^{\mathsf{T}}\mathbf{q}_{i,0} - \mathrm{q}^{\mathrm{set}}_{i,0} - E_{i_q} - r_{\eta_i}\eta_i\right)\right)$
        $\psi_i^+ = \mathcal{P}_{\geq 0}\left(\psi_i + \alpha_{\psi_i}\left(\mathrm{q}^{\mathrm{set}}_{i,0} - \mathbb{1}^{\mathsf{T}}\mathbf{q}_{i,0} - E_{i_q} - r_{\psi_i}\psi_i\right)\right)$
        $\boldsymbol{\gamma}_i^+ = \mathcal{P}_{\geq 0}\left(\boldsymbol{\gamma}_i + \alpha_{\gamma_i}\left(\mathbf{v}_i - \overline{\mathbf{v}}_i - r_{\gamma_i}\boldsymbol{\gamma}_i\right)\right)$
        $\boldsymbol{\nu}_i^+ = \mathcal{P}_{\geq 0}\left(\boldsymbol{\nu}_i + \alpha_{\nu_i}\left(\underline{\mathbf{v}}_i - \mathbf{v}_i - r_{\nu_i}\boldsymbol{\nu}_i\right)\right)$
        $\boldsymbol{\zeta}_i^+ = \mathcal{P}_{\geq 0}\left(\boldsymbol{\zeta}_i + \alpha_{\zeta_i}\left(\mathbf{i}_i - \bar{\mathbf{i}}_i - r_{\zeta_i}\boldsymbol{\zeta}_i\right)\right)$
    [Step 4]: LC updates (V)DER set-points
        $\mathbf{x}_i^+ = \underset{\mathbf{x}_i \in \boldsymbol{\mathcal{X}}_i}{\arg\min}\, L_i^{\mathrm{r}}(\mathbf{x}_i, \mathbf{d}_i^+; \mathbf{x}_{\mathsf{P}(i)})$
    [Step 5]: Transmit set-points to LCs of each child area
        $\mathrm{p}^{\mathrm{set}}_{j,0}(\mathbf{x}_i^+) = T^{\mathrm{p}}_j \mathbf{x}_i^+, \quad \mathrm{q}^{\mathrm{set}}_{j,0}(\mathbf{x}_i^+) = T^{\mathrm{q}}_j \mathbf{x}_i^+, \qquad j \in \mathsf{C}(i).$
```

Design Features

- **Local measurements** used only by **local** controller (minimize delay)
- Local control requires only **local grid sensitivity model** (e.g., $\mathbf{p}_{i,0} = \mathbf{A}_i \mathbf{x}_i$, etc.)
- Real-time feedback confers **robustness** to model uncertainty; stability guarantees
- Computationally simple, systematically tunable
- Scalable to **arbitrary numbers** of coordinated areas





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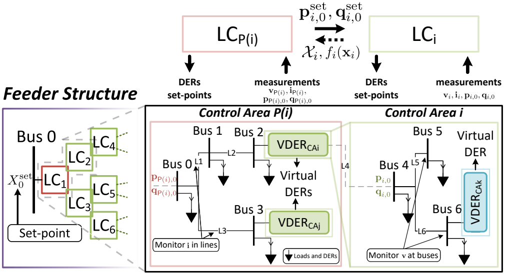

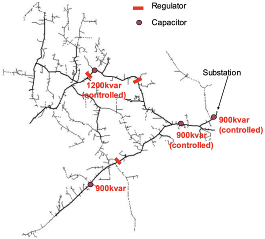

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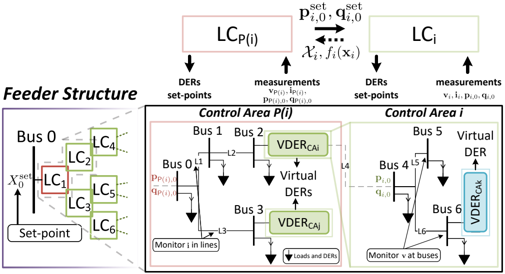

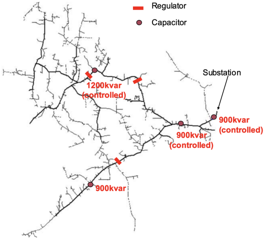

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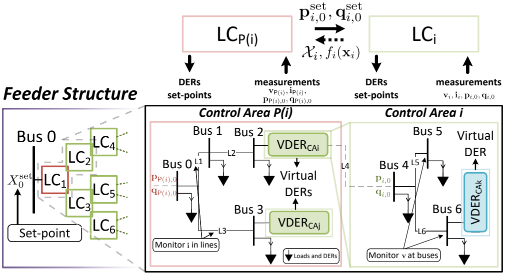

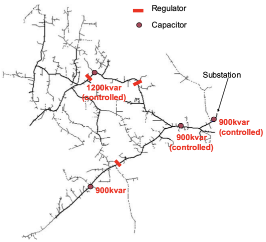

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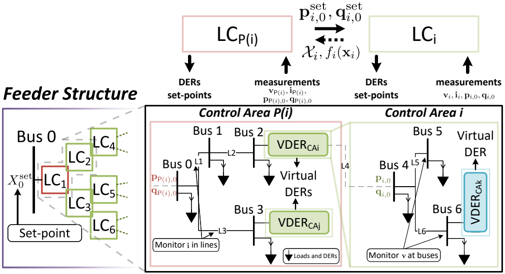
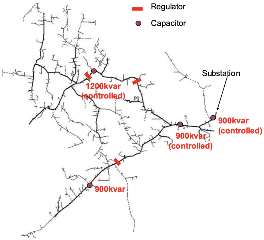
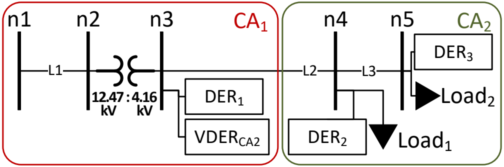
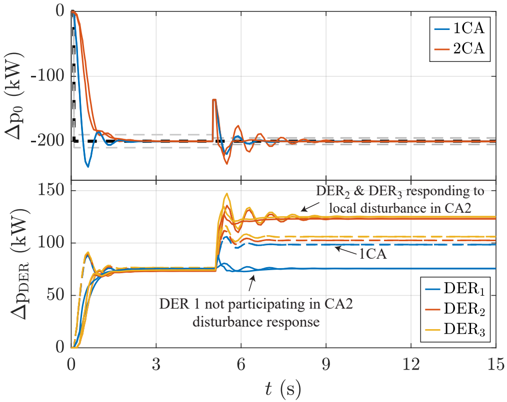




Toy Example: Five-Bus Feeder, 200kW Request



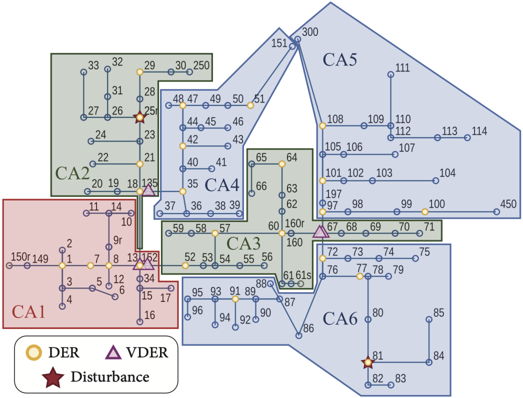


DER_2 & DER_3 responding to local disturbance in CA2

1CA

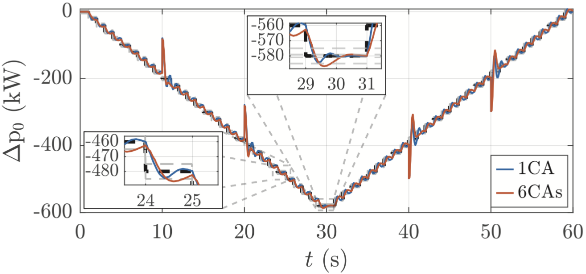
DER 1 not participating in CA2 disturbance response

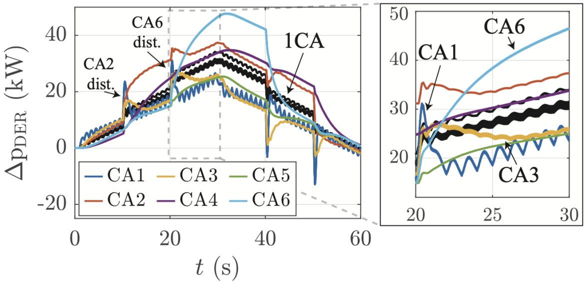
Example: 123 Bus Feeder



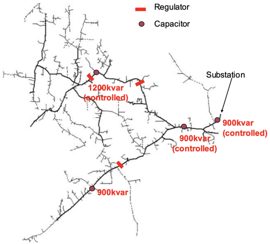
- 6 Control Areas
- 17 DERs
- Track **ramp signal** from TSO

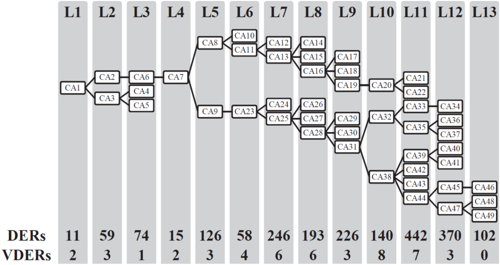
Example: 123 Bus Feeder





Example: 8500 Bus Feeder





	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13
DERs	11	59	74	15	126	58	246	193	226	140	442	370	102
VDERs	2	3	1	2	3	4	6	6	3	8	7	3	0

- 49 Control Areas
- 13 Nested Levels
- 2062 DERs (mix of 1ϕ, 2ϕ, and 3ϕ-connected) with ≈ 1s response time
- Track ramp signal from TSO

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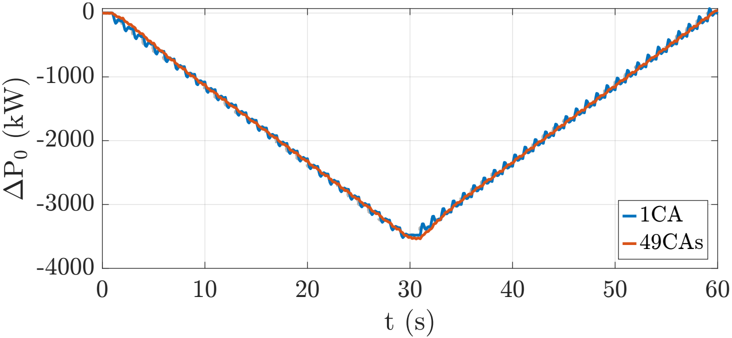

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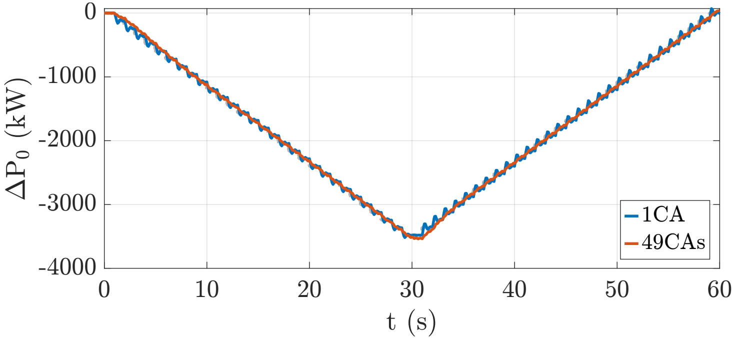

Our Next Goal: Demonstrate integration of this TN-DN coordination scheme with transmission-level fast frequency controller.

Conclusions

- Fast frequency and voltage control using TN-connected IBRs
- Fast, hierarchical, and scalable TN-DN coordination
- **Next:** Integration of controllers

Opportunities at $\{\textbf{control}\} \cap \{\textbf{energy systems}\} \cap \cdots$

- Control architecture design
- Data-driven and learning-based control w/ guarantees . . .

Parting thoughts:

- *Now is the moment for control to impact grid operations*
- Should control architectures mirror market architectures?
- Reliability/resilience must remain king

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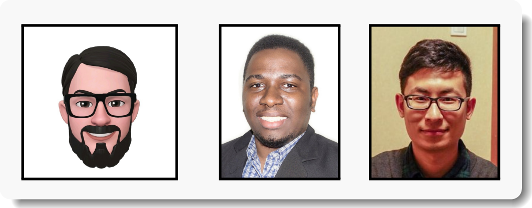
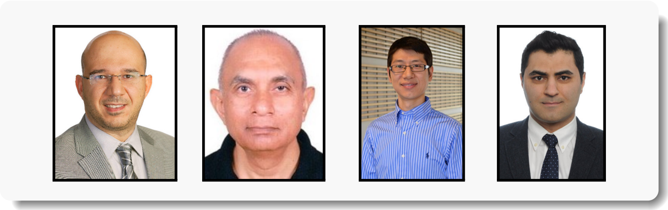
Collaborators

I. Farhat (PhD), E. Ekomwenrenren (PhD), Z. Tang (PDF)



EPRI: E. Farantatos, M. Patel, L. Zhu, A. Haddadi



Questions

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appendix

A Problem of Scale

- In North America *balancing authorities* are the current “control areas”.