Learning Coherent Clusters in Weakly Connected Power Networks

From Coherence to Frequency Control for High IBR Grids

Enrique Mallada

JOHNS HOPKINS UNIVERSITY

Autonomous Energy Systems Workshop

NREL, Golden, Colorado

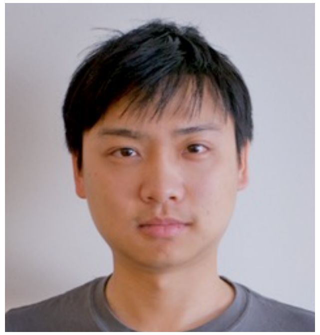
September 16, 2023

Acknowledgements

Students

Yan Jiang

UNIVERSITY of WASHINGTON



Hancheng Min

Eliza Cohn

JOHNS HOPKINS UNIVERSITY

Collaborators

Petr Vorobev

Skoltech

Skolkovo Institute of Science and Technology

Richard Pates

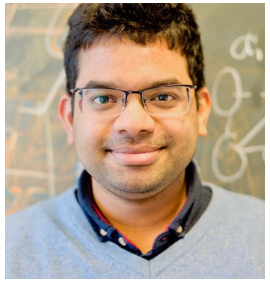
LUND UNIVERSITY

Fernando Paganini

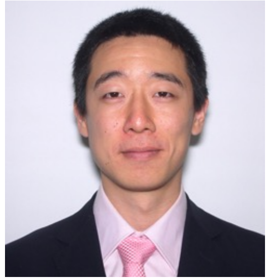
ORT UNIVERSIDAD ORT Uruguay

Dominic Groß

WISCONSIN UNIVERSITY OF WISCONSIN–MADISON



Bala K. Poolla



Yashen Lin

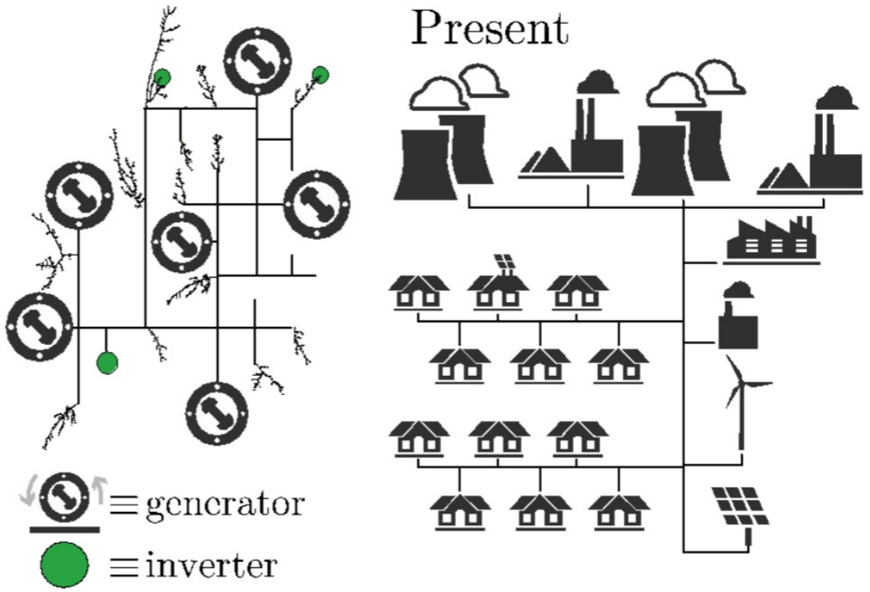
NREL NATIONAL RENEWABLE ENERGY LABORATORY

Andrey Bernstein

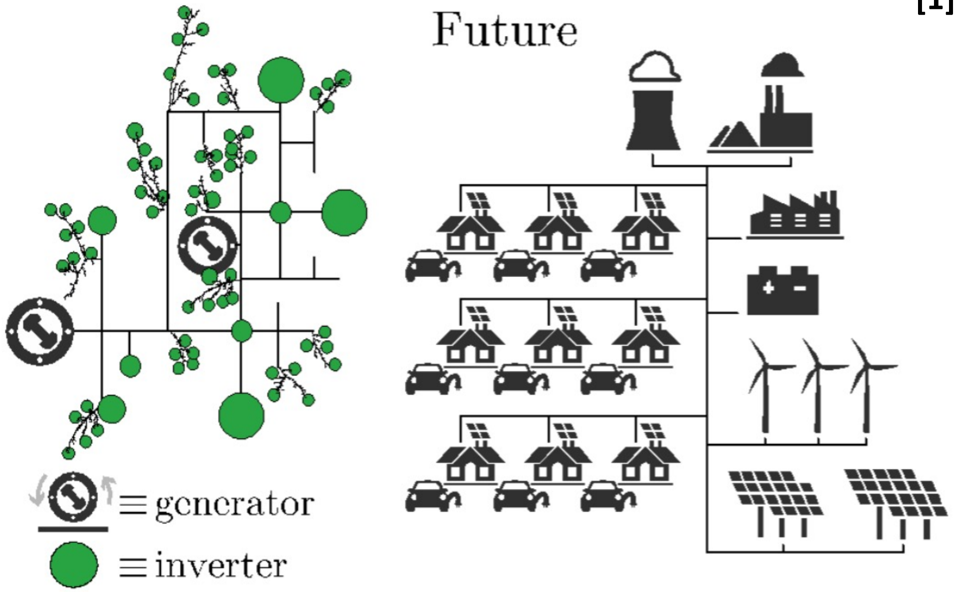
NSF

DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

The Future Grid



*[1]



Present grid

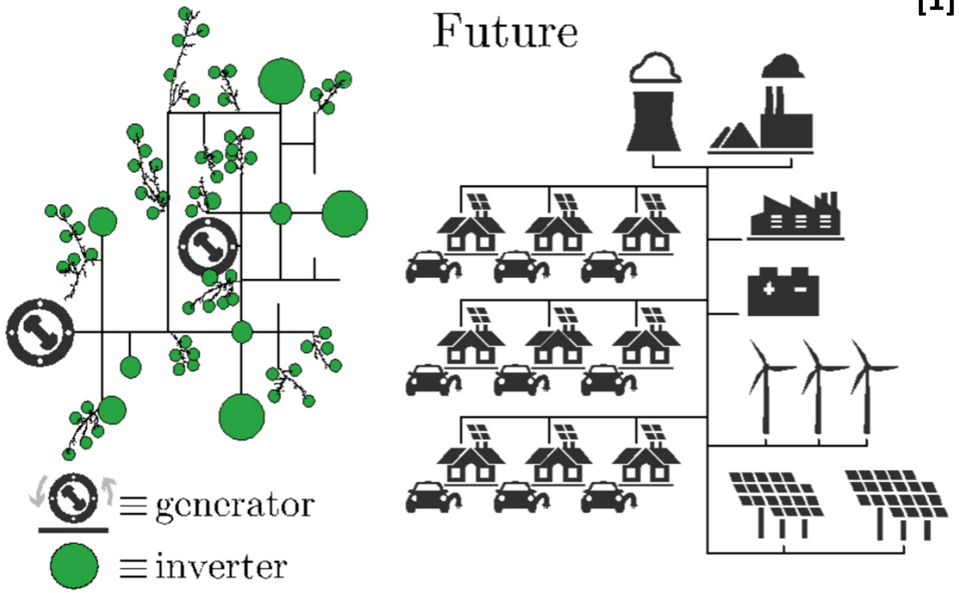
- dispatchable generation
- high inertial response
- strong voltage support
- well known physics

Future

- variable and distributed generation
- limited inertia levels
- weak voltage support
- proprietary control laws (black box)

[1] Lin et al. Research roadmap on grid-forming inverters. Technical report, National Renewable Energy Lab.(NREL), Golden CO, 2020

The Future Grid



*[1]

Future

- variable and distributed generation
- limited inertia levels
- weak voltage support
- proprietary control laws (black box)

Selected challenges

- increased system **uncertainty**
- **sensitivity** to disturbances
- new forms of **instabilities**, induced by inverter-based resources
- need to compensate for **reduced inertia**

Research questions:

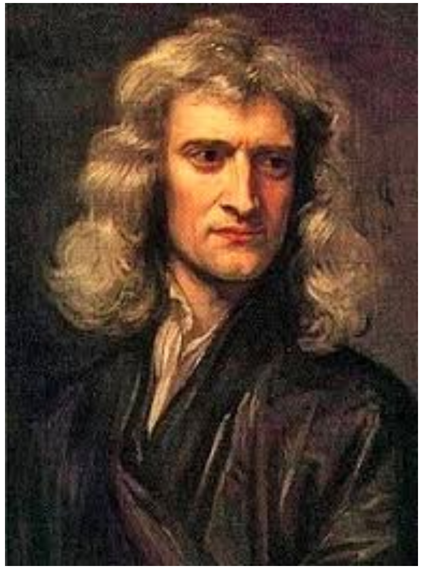
- How should we control a grid with limited inertial/voltage support?
- Should we try to mimic SGs response? Or find new and more efficient control paradigms, suitable for IBRs?

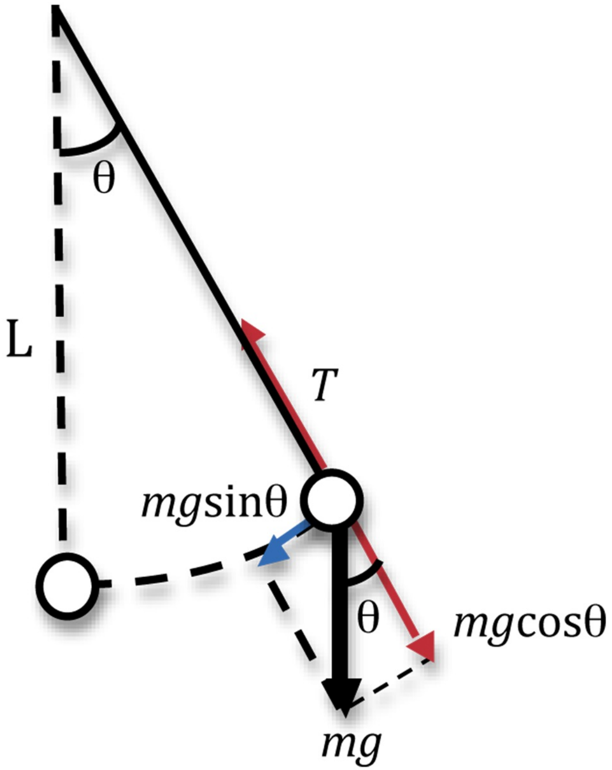
[1] Lin et al. Research roadmap on grid-forming inverters. Technical report, National Renewable Energy Lab.(NREL), Golden CO, 2020

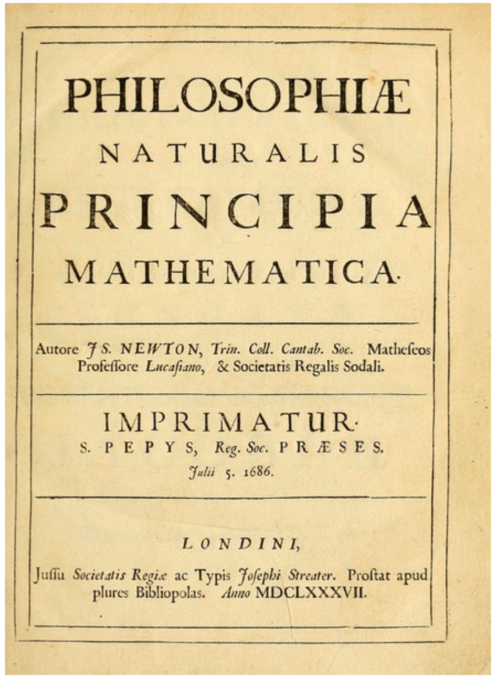
Outline

- Merits and trade-offs of low inertia
  - Control Perspective: Lighter systems are easier to control!
- Analysis of Weakly-Connected Coherent Networks
  - Generalized Center of Inertia captures IBR dynamics
  - Identification of coherent modes via spectral clustering
- Grid Shaping Control
  - Grid-following/forming control framework for controlling future girds

Merits and Tradeoffs of Inertia






PHILOSOPHIÆ

NATURALIS

PRINCIPIA

MATHEMATICA.

Autore J S. NEWTON, Trin. Coll. Cantab. Soc. Matheſeos Profeſſore Lucaſiano, & Societatis Regalis Sodali.

IMPRIMATUR.

S. PEPYS, Reg. Soc. PRÆSES.

Julii 5. 1686.

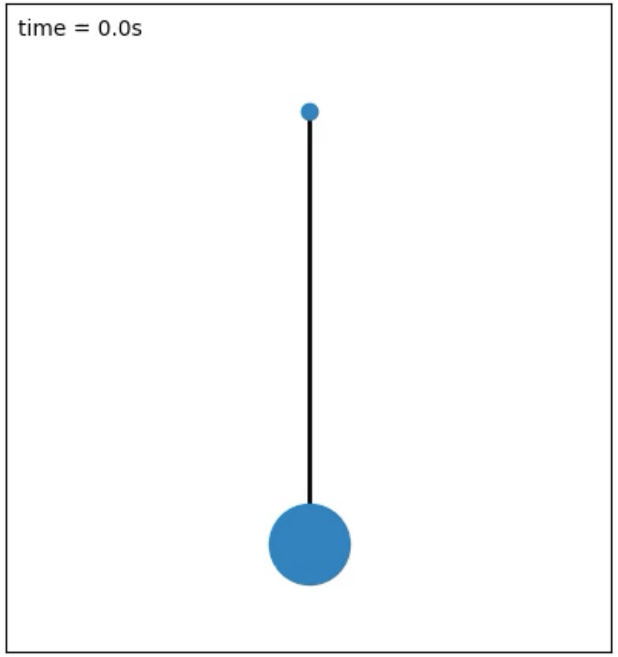
LONDINI,

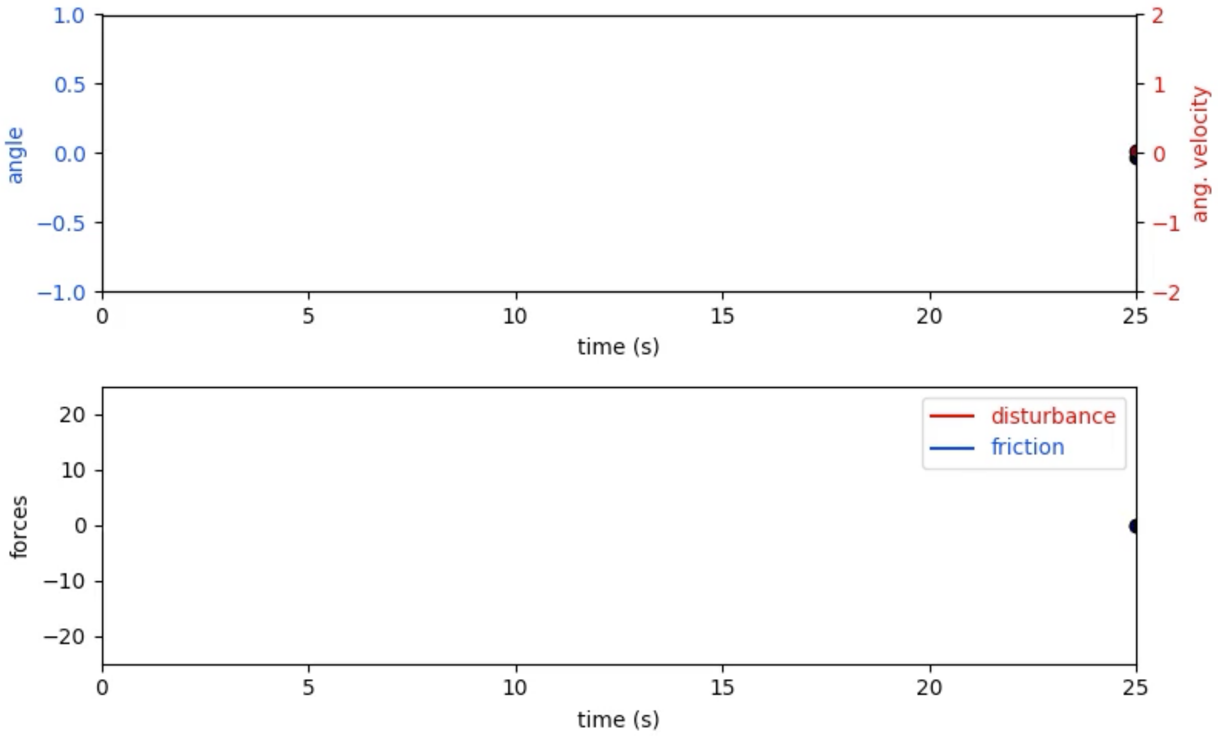
Juſſu Societatis Regiæ ac Typis Joſephi Streater. Proſtat apud plures Bibliopolas. Anno MDCLXXXVII.

$$\ddot{\theta} = -\frac{d}{m}\dot{\theta} - g\sin\theta + \frac{f}{m}$$

Merits and Trade-offs of Inertia

$$\ddot{\theta} = -\frac{d}{m}\dot{\theta} - g\sin\theta + \frac{f}{m}$$



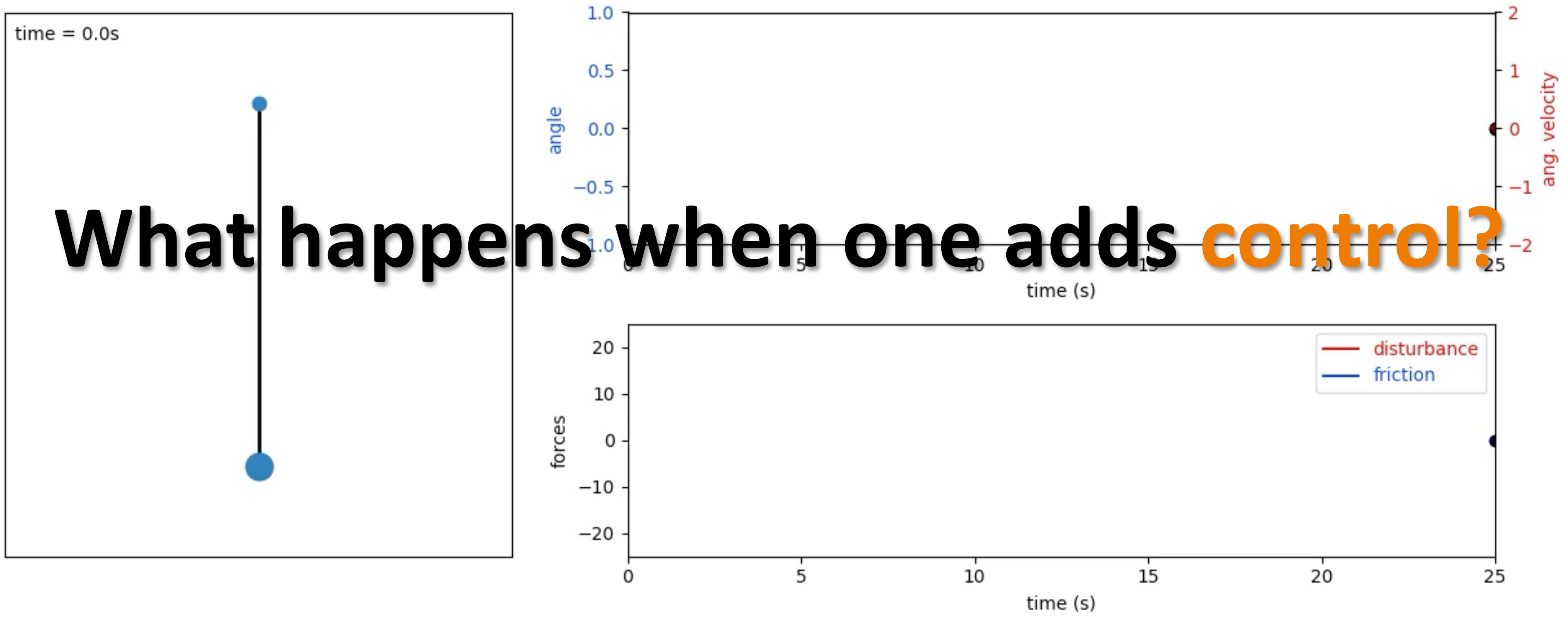


Pros: Provides natural disturbance rejection

Cons: Hard to regain steady-state

Merits and Trade-offs of Low Inertia

$$\ddot{\theta} = -\frac{d}{m}\dot{\theta} - g\sin\theta + \frac{f}{m}$$



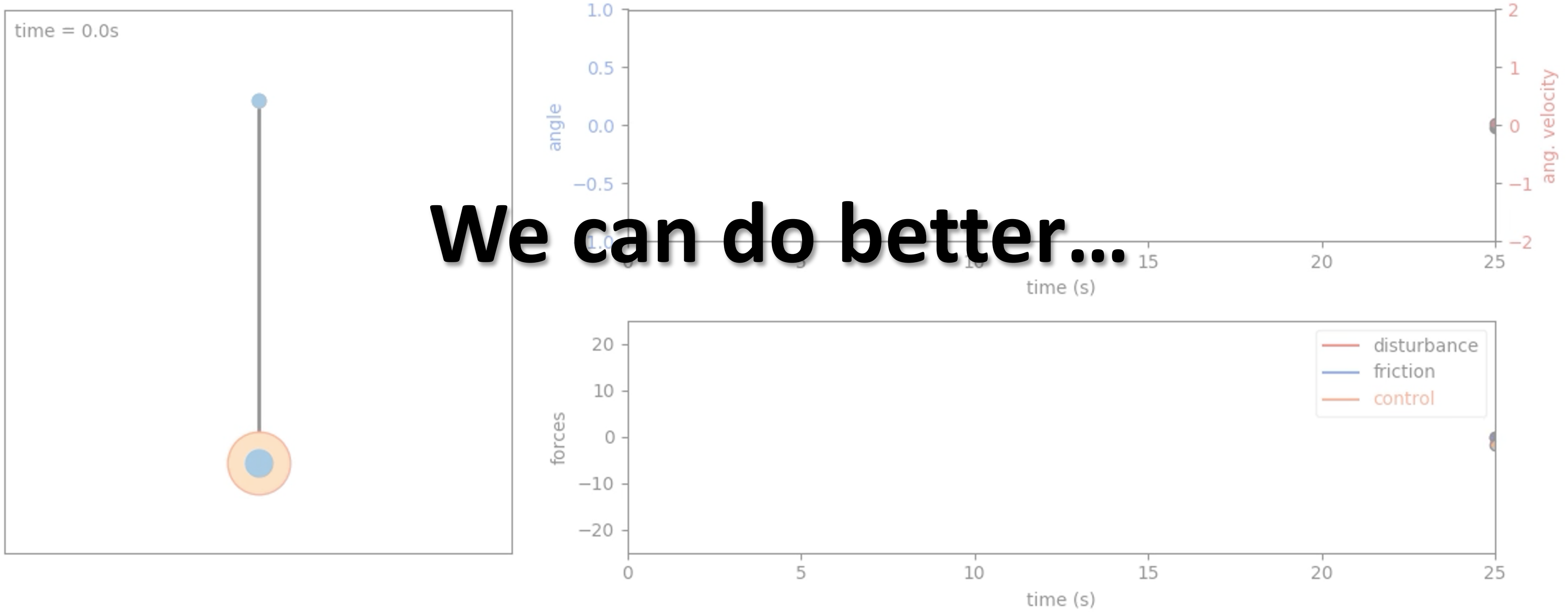
What happens when one adds control?

Cons: Susceptible to disturbances

Pros: Regains steady-sate faster

Control of Low Inertia Pendulum

Virtual Mass Control: $m\ddot{\theta} = -d\dot{\theta} - mg\sin\theta + f - \nu\ddot{\theta}$



We can do better…

Pros:

Provides disturbance rejection

Cons:

Hard to regain steady-state + **excessive control effort**

Control of Low Inertia Pendulum

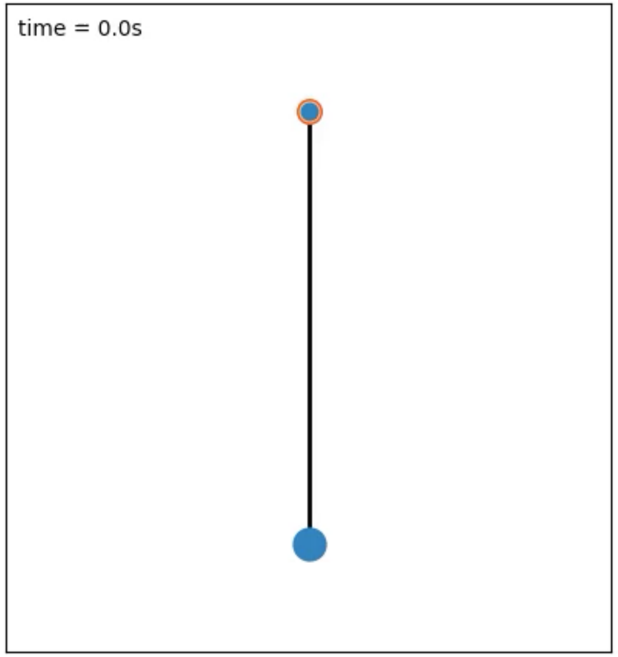

Yan Jiang

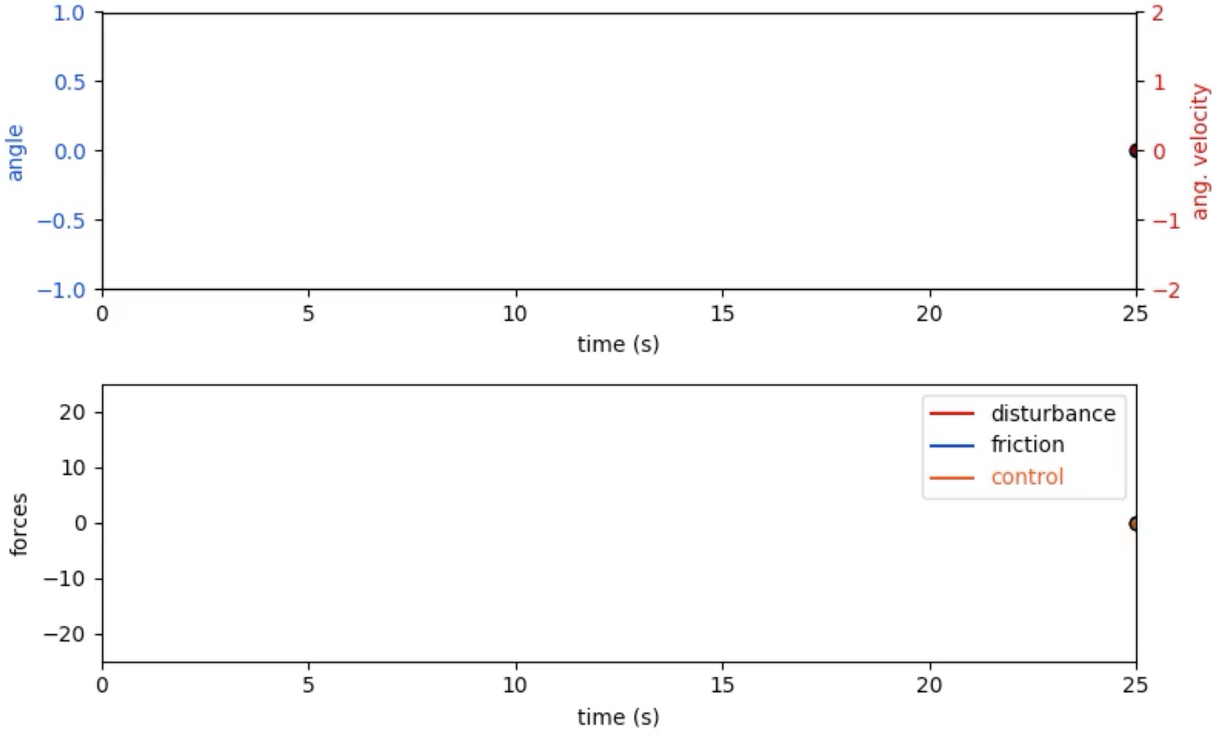

Richard Pates

Dynamic Droop:

$$m\ddot{\theta} = -d\dot{\theta} - mg\sin\theta + f + x$$

$$\tau'\dot{x} = -x - (r_r^{-1}\dot{\theta} + \tau'\nu'\ddot{\theta})$$





[TAC 21] Jiang, Pates, M, *Dynamic droop control in low inertia power systems*, **IEEE Transactions on Automatic Control, 2021**

Control of Low Inertia Pendulum

Yan Jiang

Richard Pates

Dynamic Droop: $$m\ddot{\theta} = -d\dot{\theta} - mg\sin\theta + f + x$$

3518 IEEE TRANSACTIONS ON AUTOMATIC CONTROL, VOL. 66, NO. 8, AUGUST 2021

Dynamic Droop Control in Low-Inertia Power Systems

Yan Jiang, Richard Pates, and Enrique Mallada, *Senior Member, IEEE*

Dynamic Droop Benefits

- Overshoot Elimination in Nadir
- Noise Attenuation
- Disturbance Rejection
- Reduce Inter-area Oscillations

Caveat

- Control design limited to co-located resources (SGs and IBRs)

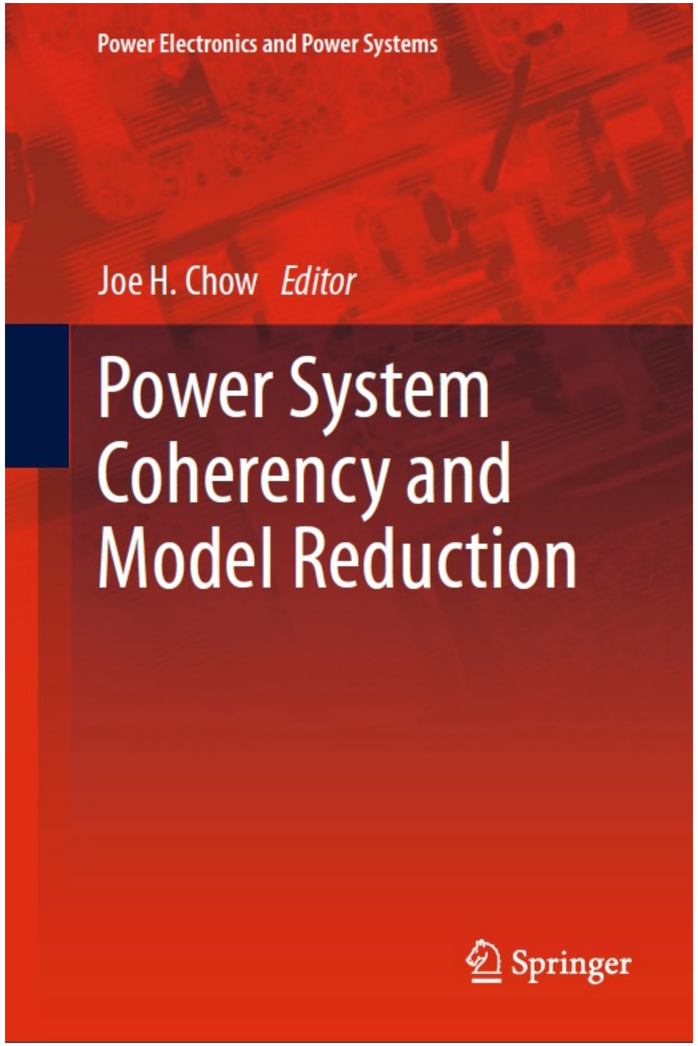
[TAC 21] Jiang, Pates, M, *Dynamic droop control in low inertia power systems*, **IEEE Transactions on Automatic Control, 2021**

Outline

- Merits and trade-offs of low inertia
    - Control Perspective: Lighter systems are easier to control!
- Analysis of Weakly-Connected Coherent Networks
    - Generalized Center of Inertia captures IBR dynamics
    - Identification of coherent modes via spectral clustering
- Grid Shaping Control
    - Grid-following/forming control framework for controlling future girds

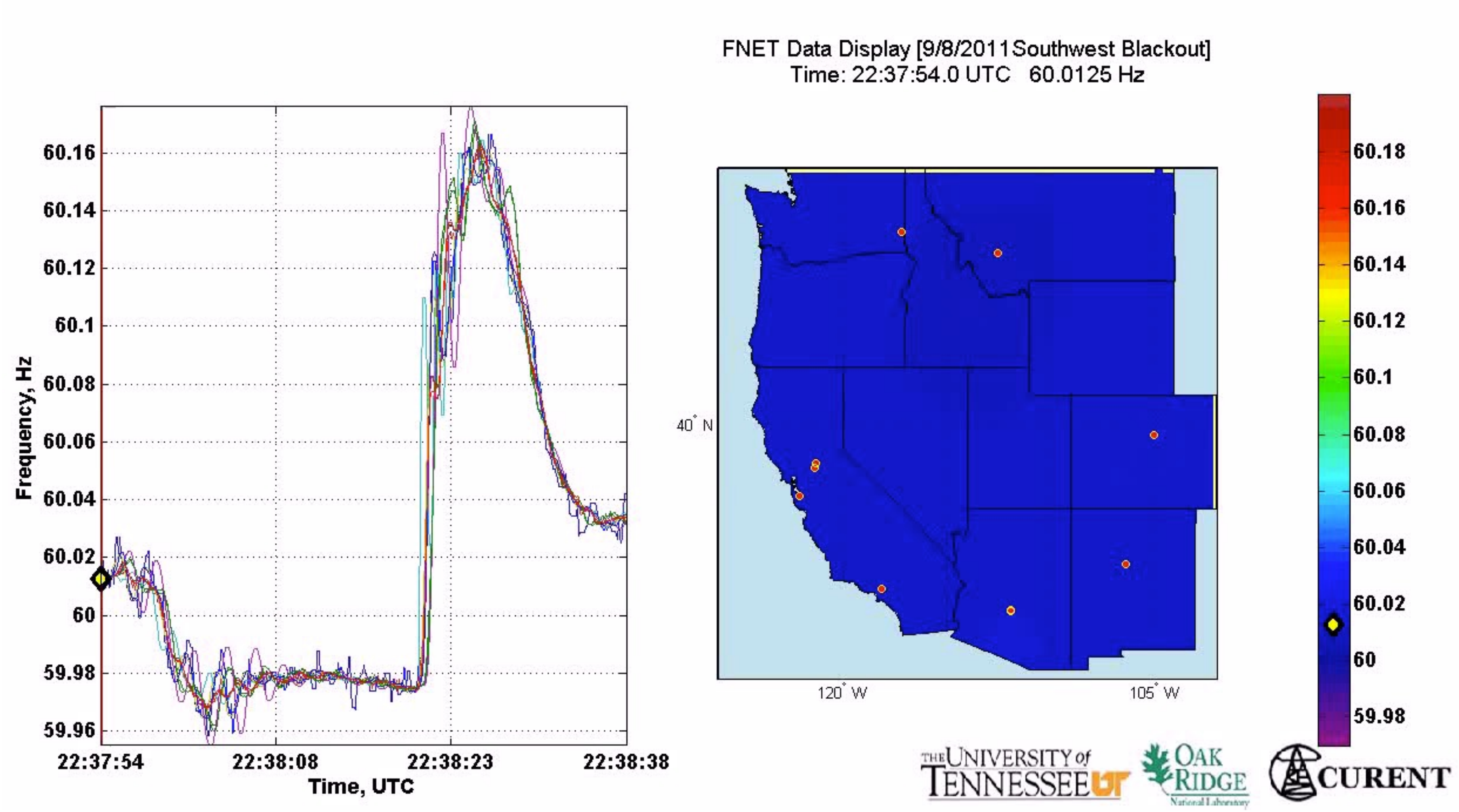
Coherence in Power Networks

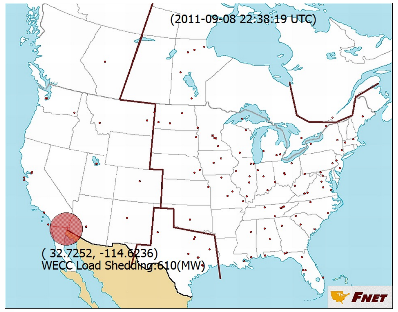
- Studied since the 70s
  - Podmore, Price, Chow, Kokotovic, Verghese, Pai, Schweppe,…
- Enables aggregation/model reduction
  - Speed up transient stability analysis
- Many important questions
  - How to identify coherent modes?
  - How to accurately reduce them?
  - What is the cause?
- Many approaches
  - Timescale separations (Chow, Kokotovic,)
  - Krylov subspaces (Chaniotis, Pai ‘01)
  - Balanced truncation (Liu et al ‘09)
  - Selective Modal Analysis (Perez-Arriaga, Verghese, Schweppe ‘82)



Goal: Understand how IBR presence affect classical coherence studies

Case Study 1: Network Coherence

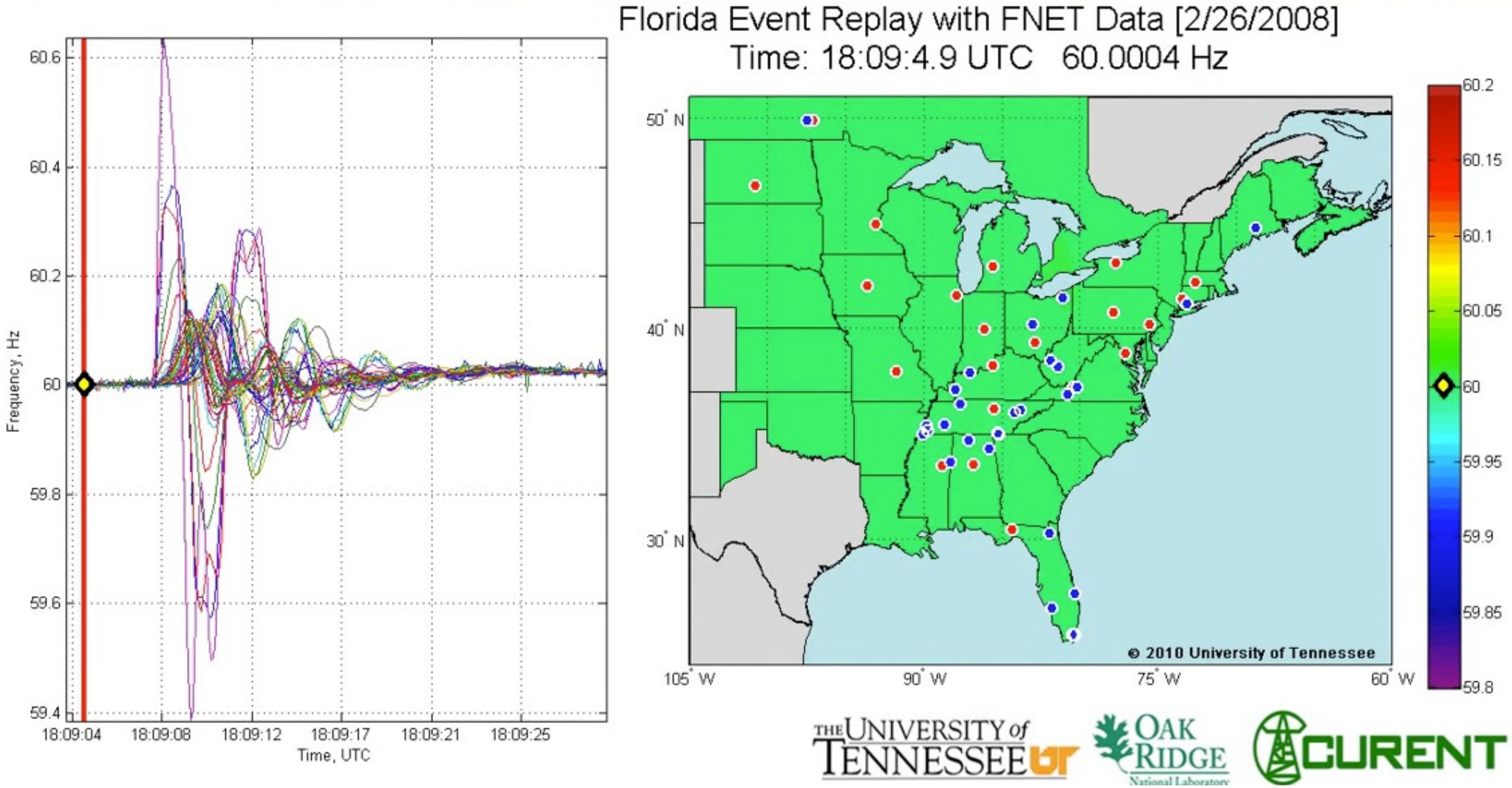




Key Questions:

- How does coherence emerge, and what does it depend on?
- How to characterize the coherent response in the presence of IBRs?

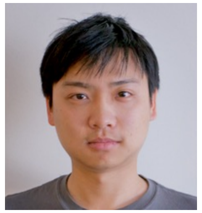
Case Study 2: Coherent Inter-area Modes



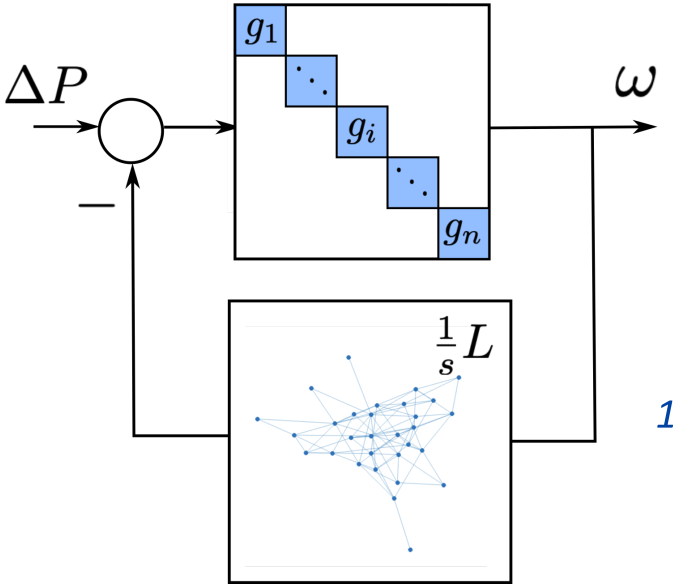
Key Questions:

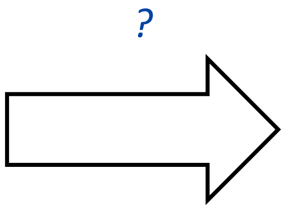
- How to identify coherent areas?
- Can we model the inter-area oscillations?

Analysis of Coherent Dynamics [CDC 19,ArXiv 23]

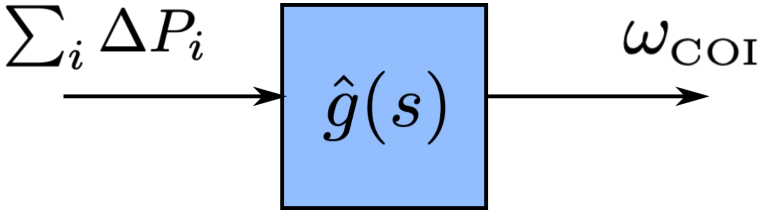



Hancheng Min Richard Pates





1.When does this network exhibit coherence?



*2.What is the exact **coherent response** of this network?*

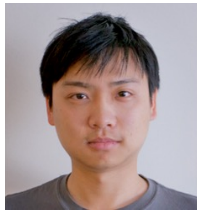
- **Problem Setup:**
- Linearized power flows L_{ij}
- Bus i: arbitrary siso tf: $\omega_i = g_i(s)\,\Delta P_i$ (SGs or IBRs)

Example I: SG + Turbine

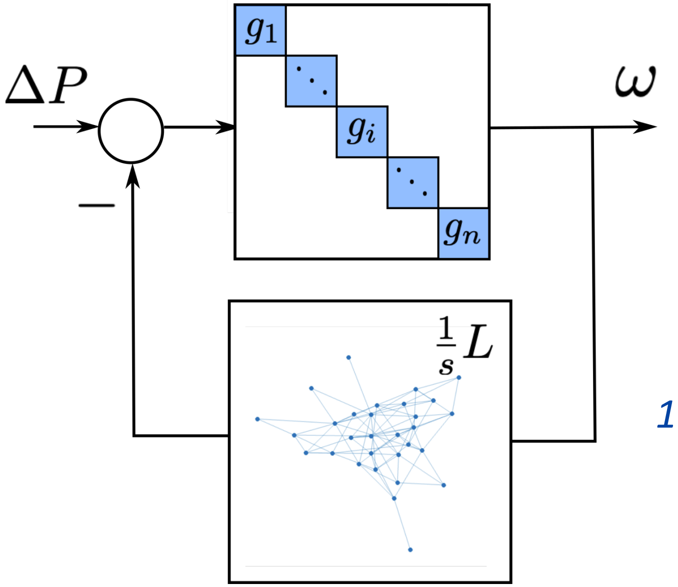
$$g_i(s) = \frac{1}{m_i s + d_i + \frac{r_i^{-1}}{\tau s + 1}}$$

[CDC 19] Min, M. Dynamics concentration of large-scale tightly-connected networks. **Conference on Decision and Control 2019**
[ArXiv 23] Min, Pates, M. A frequency domain analysis of slow coherency in networked systems. arXiv:2302.08438, **2023, submitted**

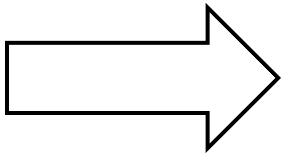
Analysis of Coherent Dynamics [CDC 19,ArXiv 23]



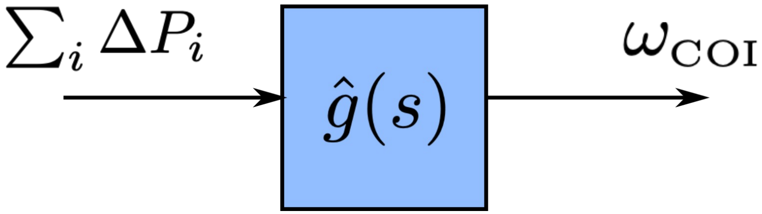

Hancheng Min **Richard Pates**



?



1.When does this network exhibit coherence?



*2.What is the exact **coherent response** of this network?*

1. Coherence can be understood as a **low rank** property the **closed-loop transfer matrix**

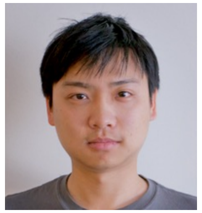
2. It emerges as the **effective algebraic connectivity** $\left|\frac{1}{s_0}\lambda_2(L)\right|$ increases

3. The coherent dynamics is given by the **harmonic sum** of bus dynamics

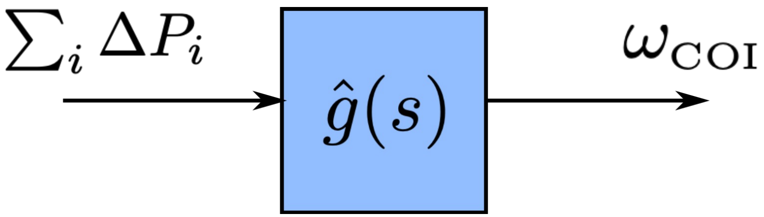
$$\hat{g}(s) = \left(\sum_{i=1}^{n} g_i^{-1}(s)\right)^{-1}$$

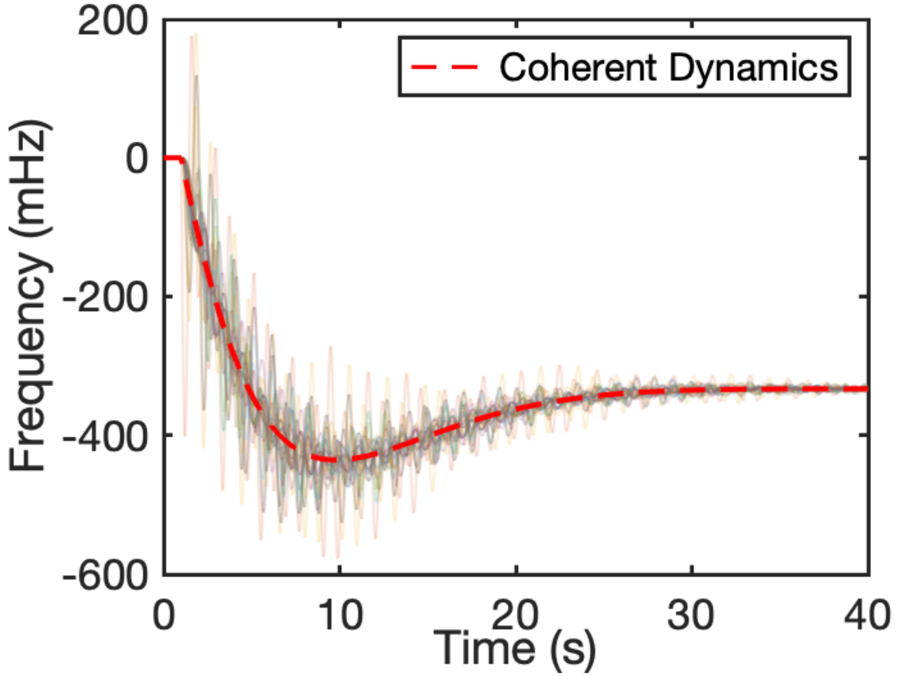
[CDC 19] Min, M. Dynamics concentration of large-scale tightly-connected networks. **Conference on Decision and Control 2019**
[ArXiv 23] Min, Pates, M. A frequency domain analysis of slow coherency in networked systems. **arXiv:2302.08438, 2023, submitted**

Generalized Center of Inertia [CDC 19,ArXiv 23]




Hancheng Min **Richard Pates**





$$\hat{g}(s) = \left(\sum_{i=1}^{n} g_i^{-1}(s) \right)^{-1}$$

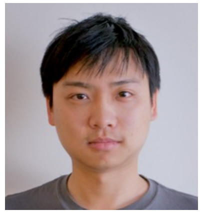
- **Coherent Dynamics: $\hat{g}(s)$**
- Representation of aggregate response
- Accuracy of approximation:
  - is frequency dependent
  - increases with network connectivity
- Provides excellent template for reduced order models (via balance-truncations)
- More details [LCSS 20]

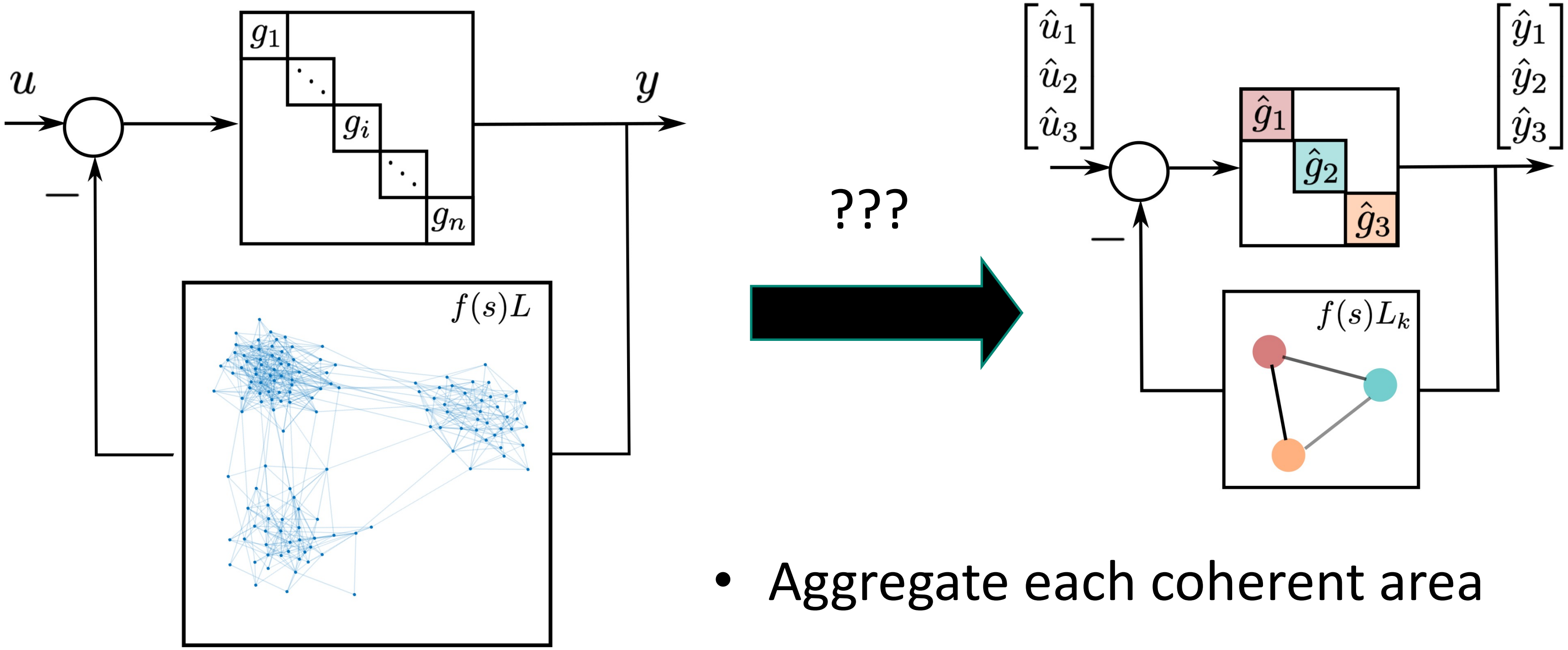
[CDC 19] Min, M. Dynamics concentration of large-scale tightly-connected networks. **Conference on Decision and Control 2019**

[ArXiv 23] Min, Pates, M. A frequency domain analysis of slow coherency in networked systems. arXiv:2302.08438, **2023, submitted**

[LCSS 20] Min, Paganini, M. Accurate reduced-order models for heterogeneous coherent generators. **IEEE LCSS 2020**

Weakly-Connected Coherent Networks



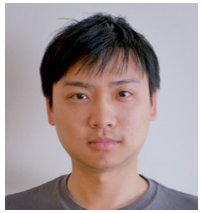


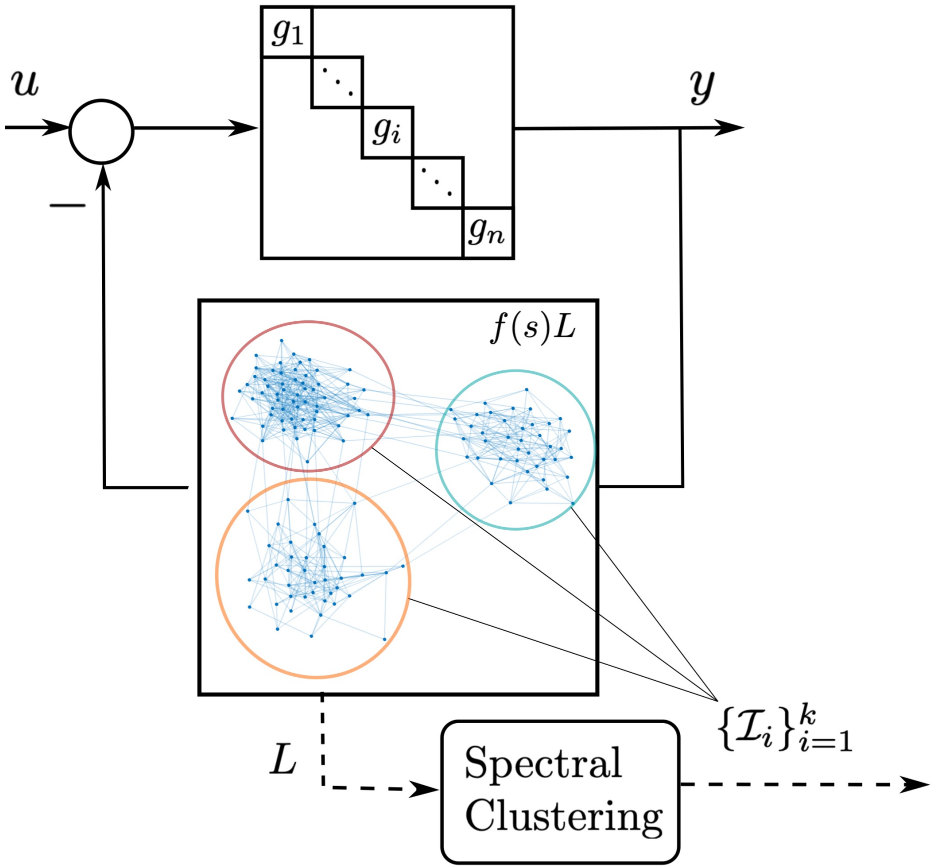
- Aggregate each coherent area
- Inter-area oscillation can be modeled as the interaction among aggregate nodes

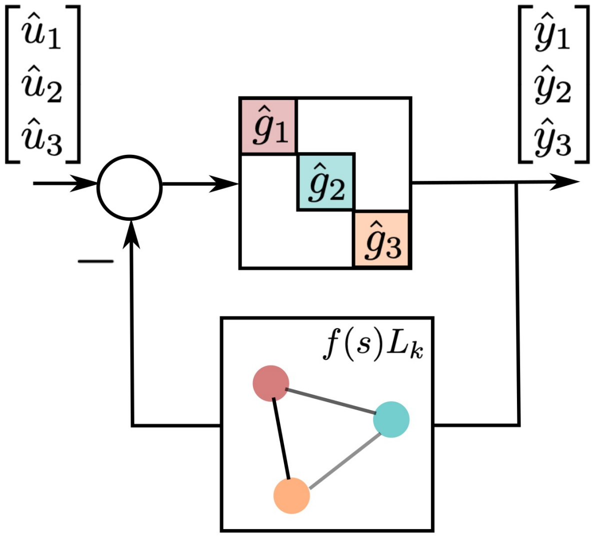
[L4DC 23] Min, M. Learning coherent clusters in weakly-connected network systems. **Leaning for Dynamics and Control 2023**

Structure-preserving Network Reduction

Step 1: **Identifying** coherent areas







Tightly-connected Networks are coherent

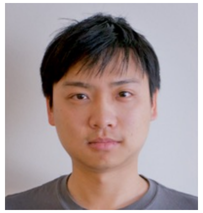
$\Downarrow$

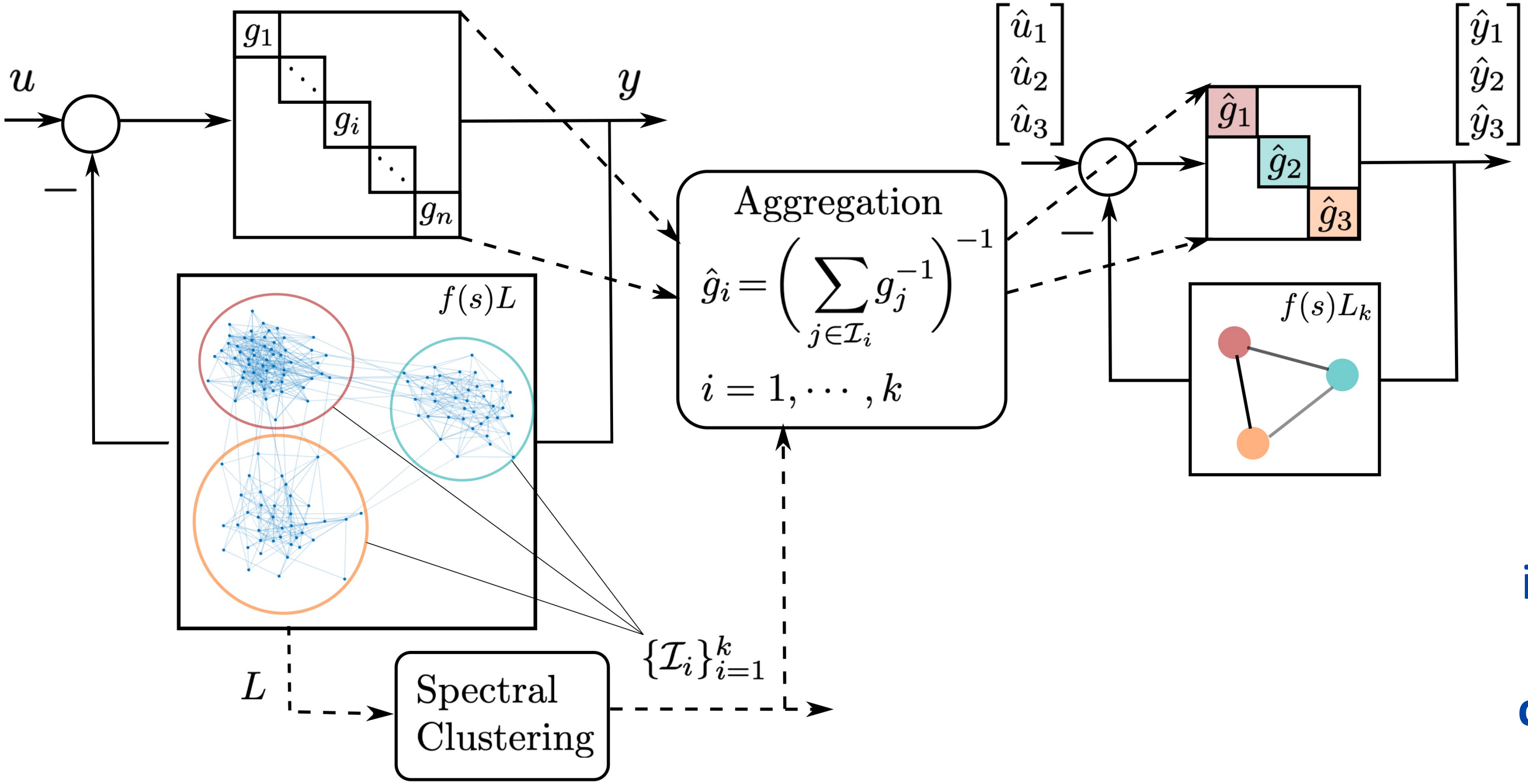
Use **spectral clustering** algorithm to **find** tightly-connected **subnetworks/areas**

[L4DC 23] Min, M. Learning coherent clusters in weakly-connected network systems. **Leaning for Dynamics and Control 2023**

Structure-preserving Network Reduction

Step 2: **Aggregate** coherent areas





Coherent dynamics are given by

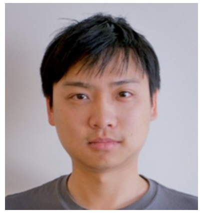
$$\hat{g}(s) = \left(\sum_{i=1}^{n} g_i^{-1}(s)\right)^{-1}$$

$$\Downarrow$$

Aggregate each identified **coherent area** into its corresponding **coherent dynamics** $\hat{g}(s)$

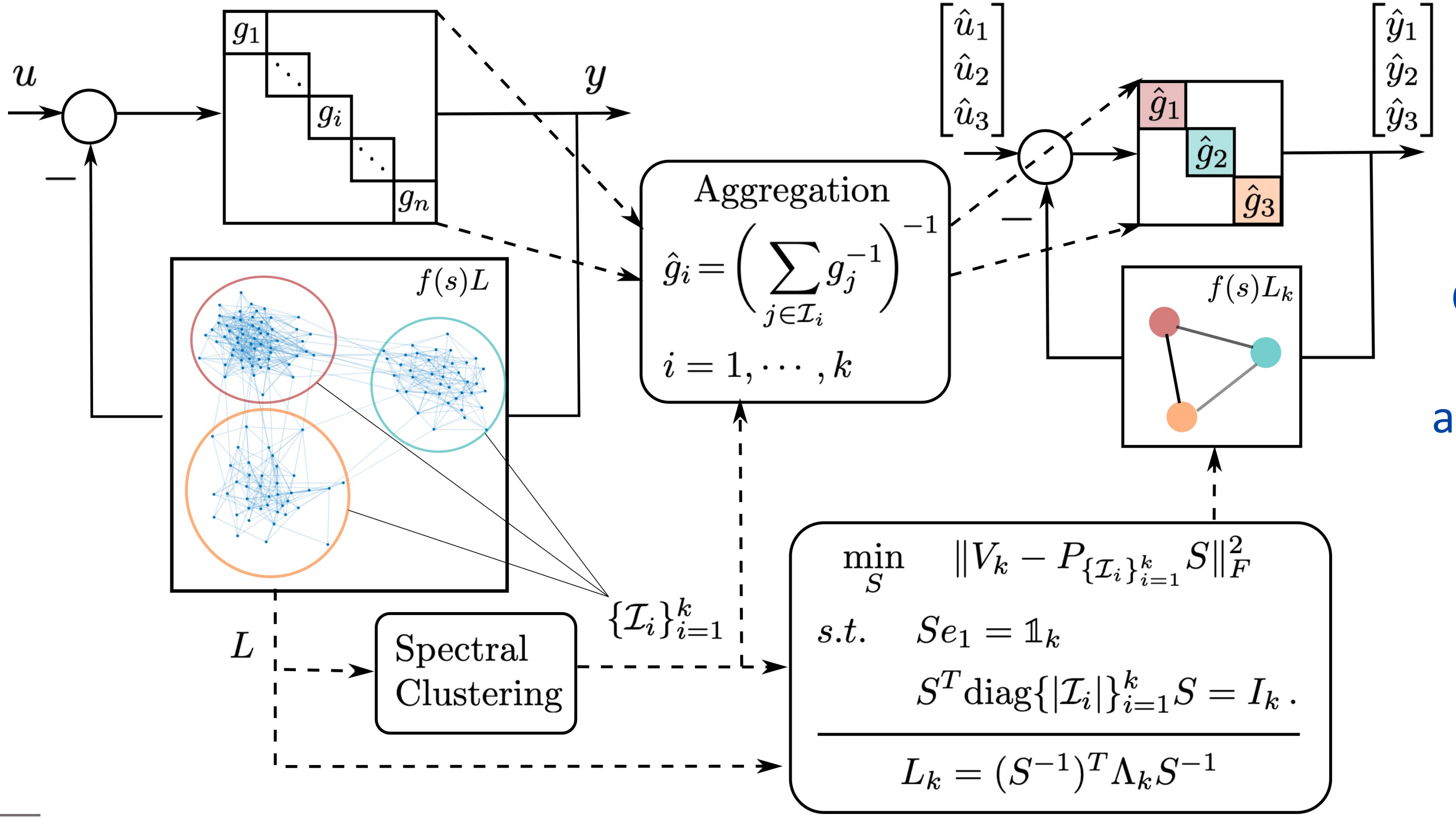
[L4DC 23] Min, M. Learning coherent clusters in weakly-connected network systems. **Leaning for Dynamics and Control 2023**

Structure-preserving Network Reduction



Hancheng Min

Step 3: Model the **interaction** among aggregate nodes

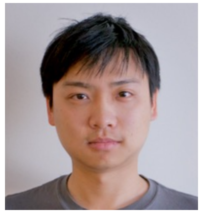


Construct the **reduced network** L_k by solving an optimization problem (it has closed-form solution)

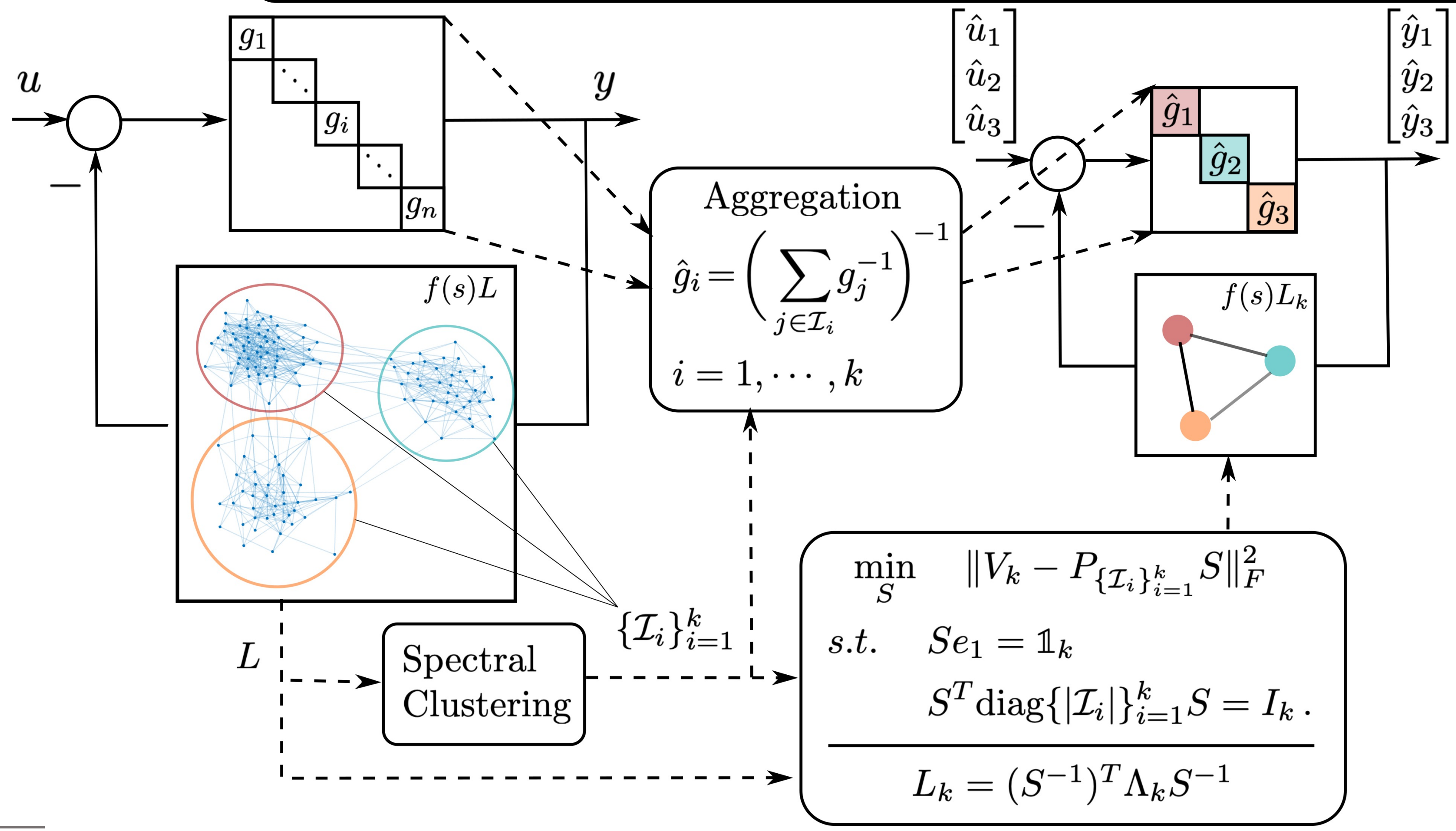
[L4DC 23] Min, M. Learning coherent clusters in weakly-connected network systems. **Leaning for Dynamics and Control 2023**

Approximation Errors

$$\left\|T(s_0) - \hat{T}_k\,(s_0)\right\|_2 = \mathcal{O}\left(\frac{1}{\lambda_{k+1}(L)}\right) + \mathcal{O}\left(\left\|V_k(L) - P_{\{I_i\}_{i=1}^k} S\right\|_2\right)$$



Hancheng Min

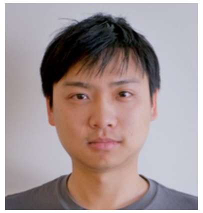


Approximation error depends on:

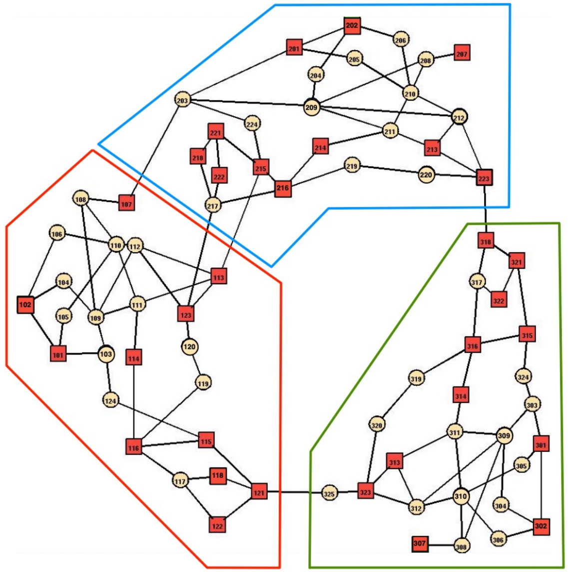
- Whether the network has a multi-cluster structure
- Whether the SC algorithm finds the right clusters
- How well one model the interaction

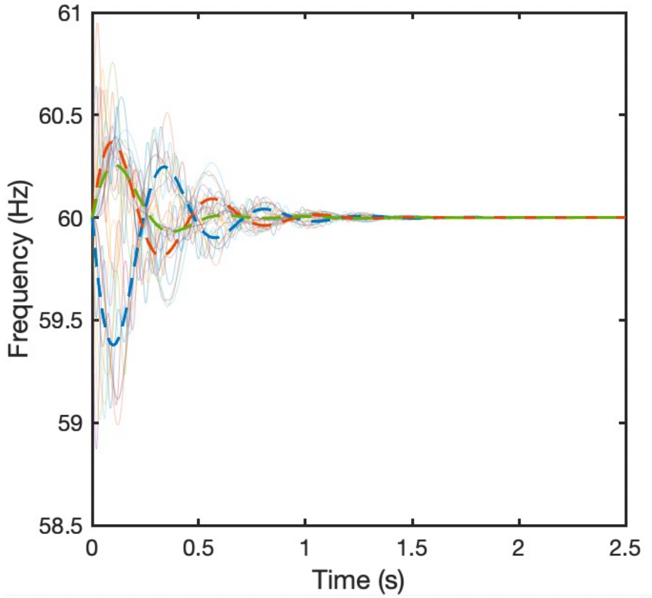
[L4DC 23] Min, M. Learning coherent clusters in weakly-connected network systems. **Leaning for Dynamics and Control 2023**

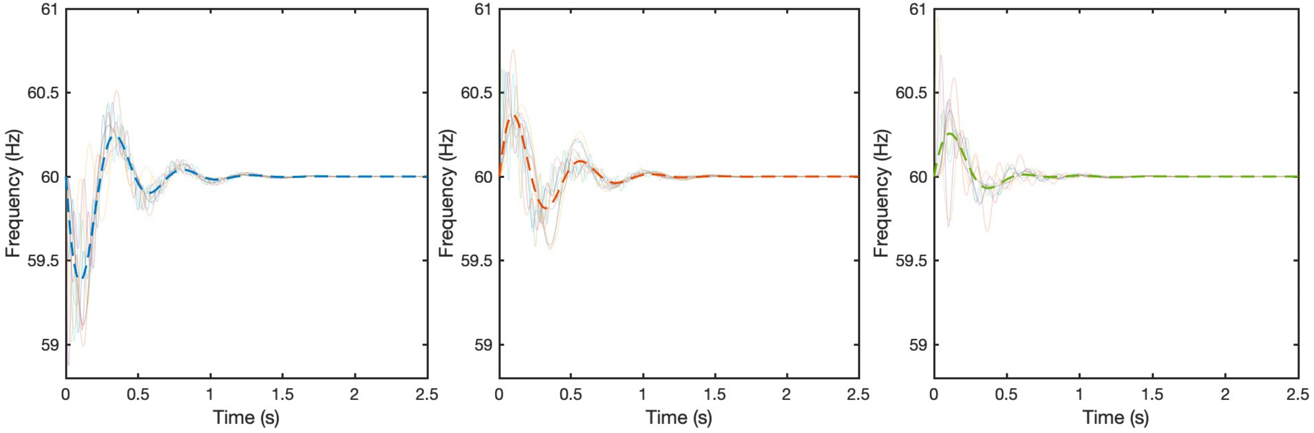
Numerical validation – RTS 96 test case



Hancheng Min







- The IEEE reliability test system: 1996
- 3 areas, 33 generators in total
- Different rotor angles across each area at initialization
- Solid lines: actual frequency response
  Dashed lines: reduced model

[L4DC 23] Min, M. Learning coherent clusters in weakly-connected network systems. **Leaning for Dynamics and Control 2023**

Outline

- Merits and trade-offs of low inertia
  - Control Perspective: Lighter systems are easier to control!
- Analysis of Weakly-Connected Coherent Networks
  - Generalized Center of Inertia captures IBR dynamics
  - Identification of coherent modes via spectral clustering
- Grid Shaping Control
  - Grid-following/forming control framework for controlling future girds

Grid Shaping Control

Use model matching control to shape system response

Grid-following IBRs

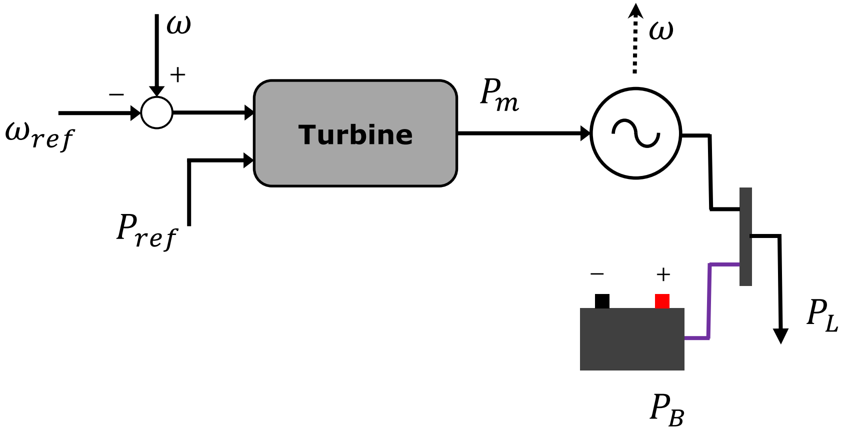
Grid-forming IBRs

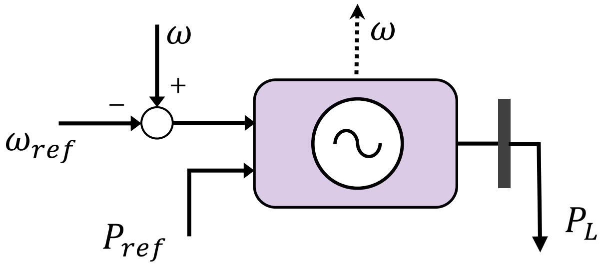
Grid-shaping with GFL IBRs [TPS 21]

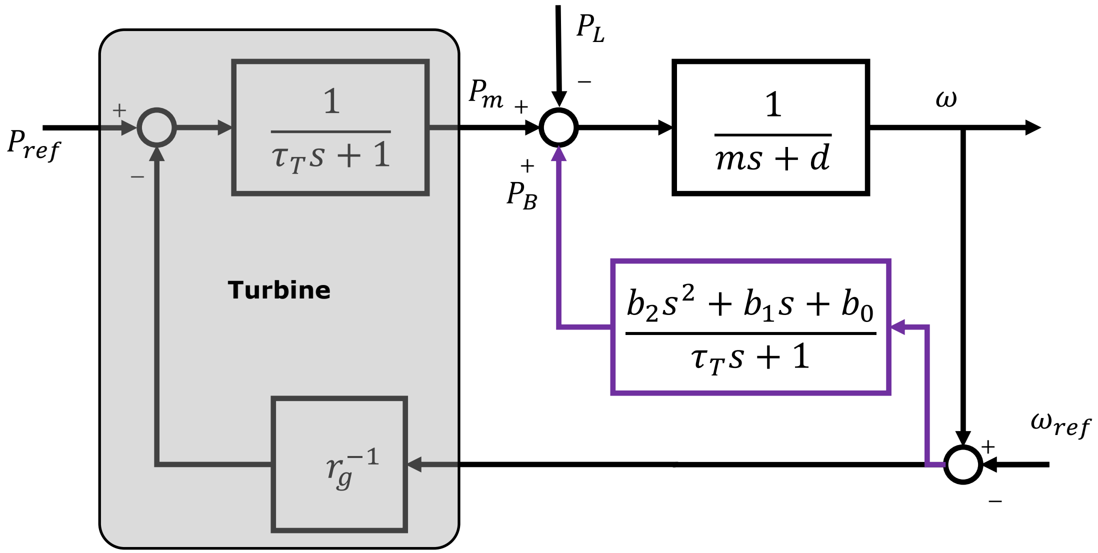

Yan Jiang

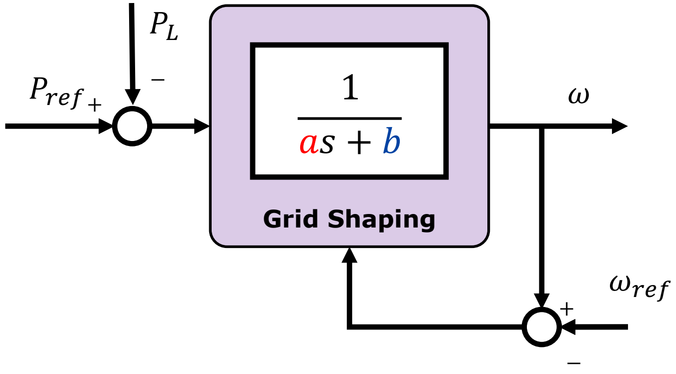

Eliza Cohn


Petr Vorobev









Tunable Performance:

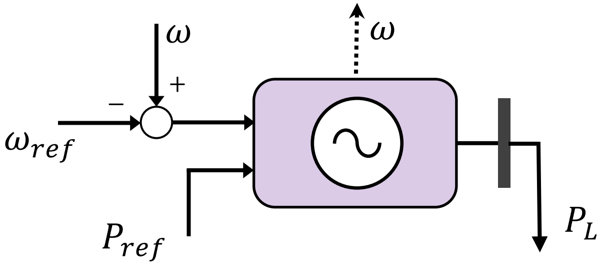
$$\text{RoCoF} = \frac{1}{a}\Delta P, \ \ \Delta\omega = \frac{1}{b}\Delta P$$

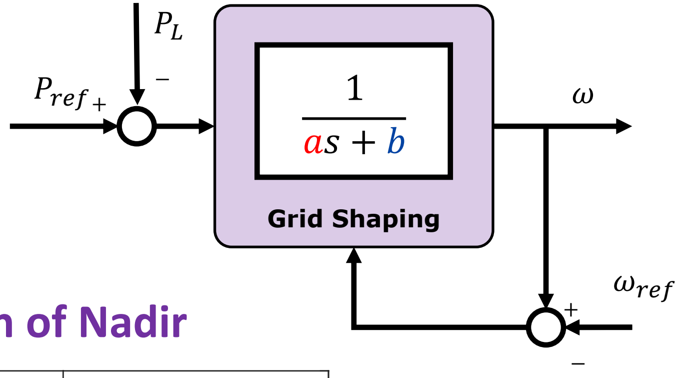
[TPS 21] Jiang, Cohn, Vorobev, M. Storage-based frequency shaping control **Transactions on Power Systems 2021**

Grid-shaping with GFL IBRs [TPS 21]



Yan Jiang Eliza Cohn Petr Vorobev

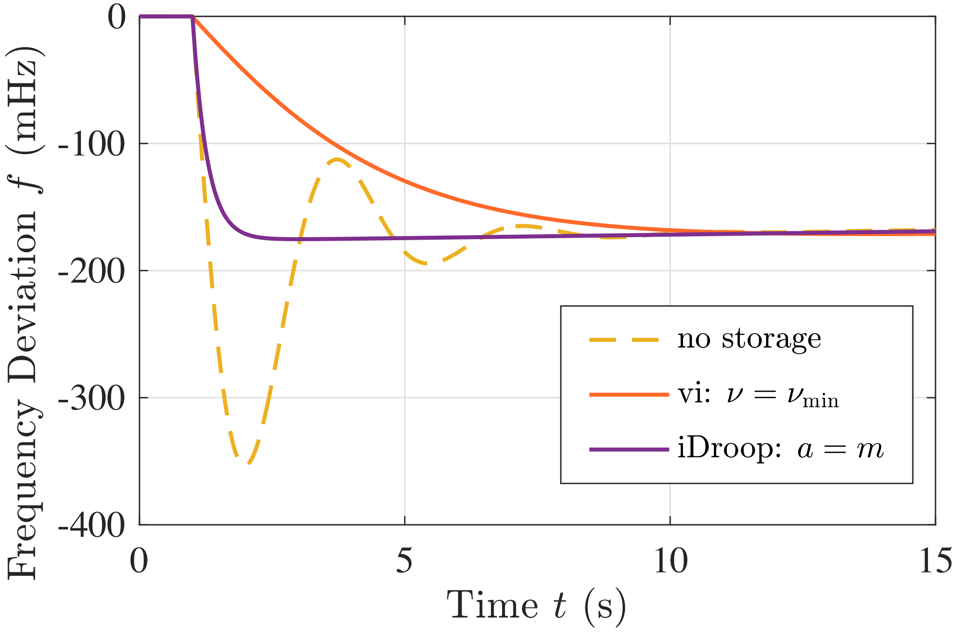


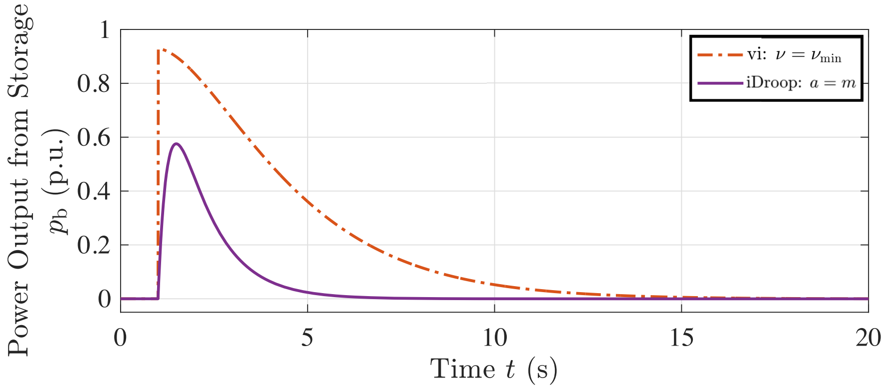


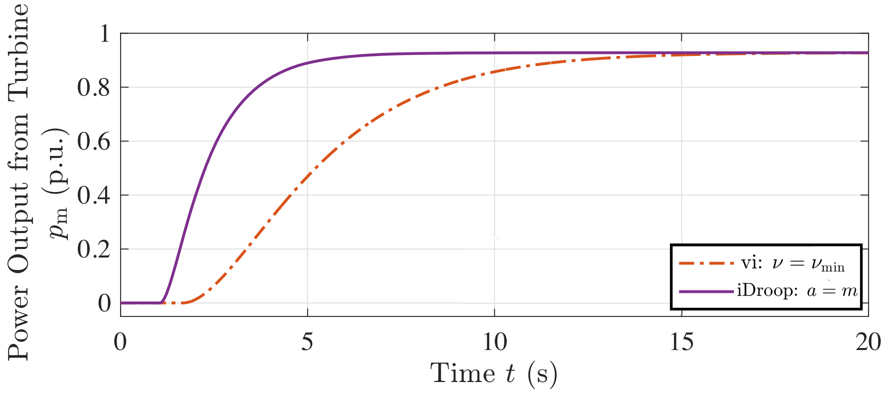
Tunable Performance:

$$\text{RoCoF} = \frac{1}{a}\Delta P, \ \Delta\omega = \frac{1}{b}\Delta P$$

Example: Efficient Elimination of Nadir





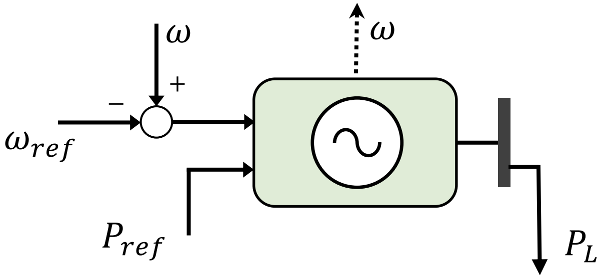


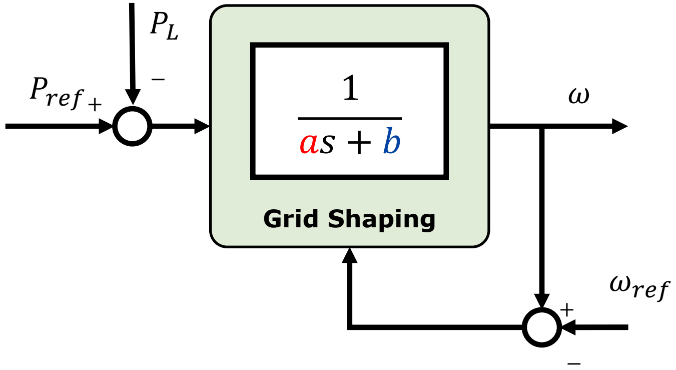
[TPS 21] Jiang, Cohn, Vorobev, M. Storage-based frequency shaping control **Transactions on Power Systems 2021**

Grid-shaping with GFL IBRs [TPS 21]



Yan Jiang   Eliza Cohn   Petr Vorobev

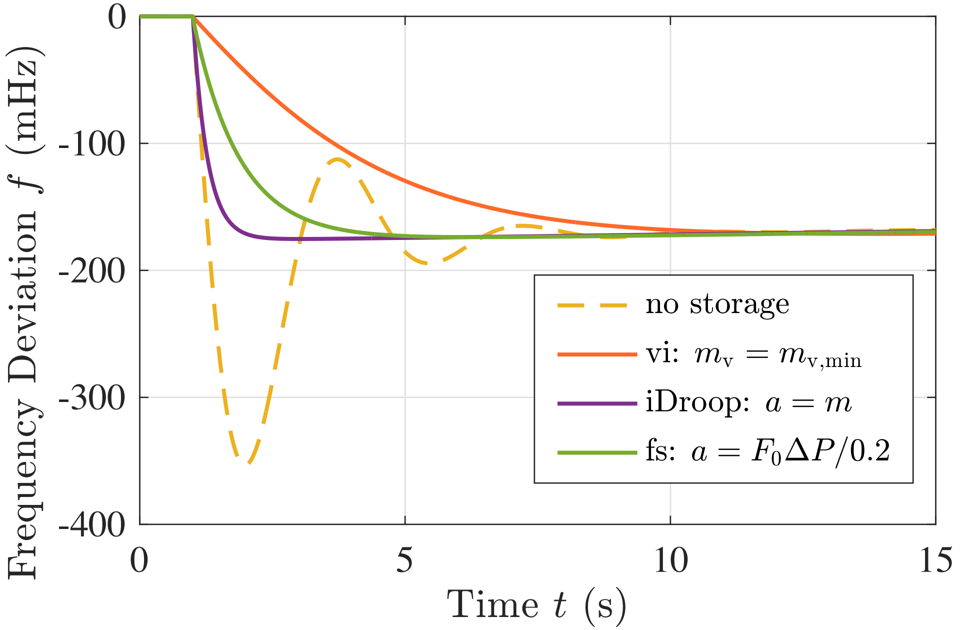




Tunable Performance:

$$\text{RoCoF} = \frac{1}{a}\Delta P,\ \ \Delta\omega = \frac{1}{b}\Delta P$$

Example II: **Tuning RoCoF**

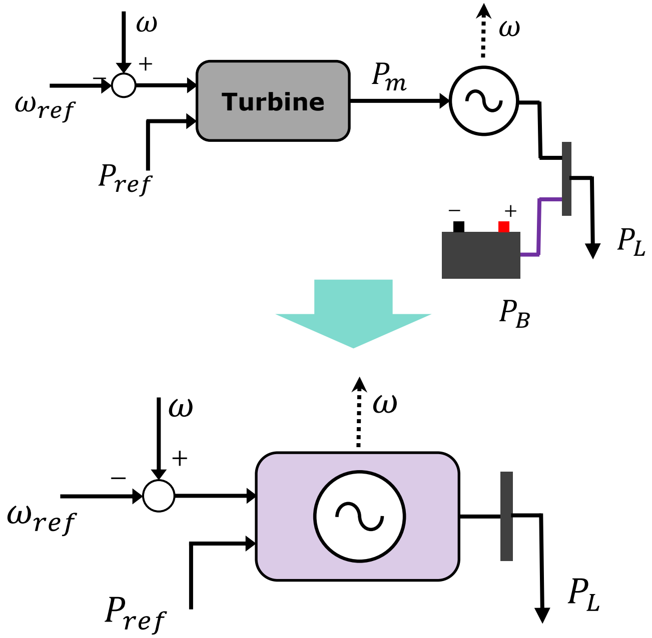


[TPS 21] Jiang, Cohn, Vorobev, M. Storage-based frequency shaping control **Transactions on Power Systems 2021**

Grid Shaping Control

Use model matching control to shape system response

Grid-following IBRs

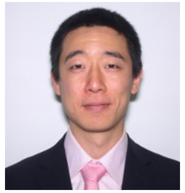


Tunable Performance:

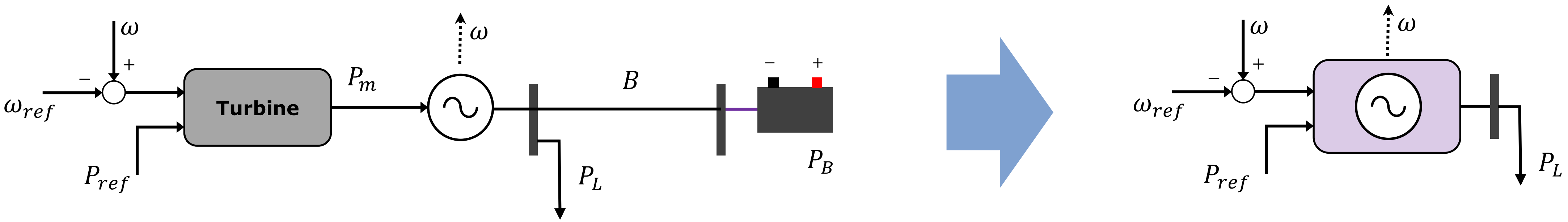
$$\text{RoCoF} = \frac{1}{a}\Delta P,\ \ \Delta\omega = \frac{1}{b}\Delta P$$

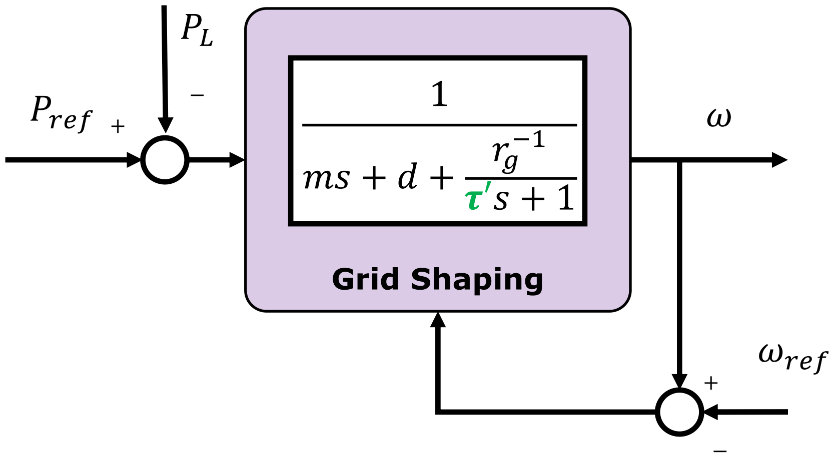
Grid-forming IBRs

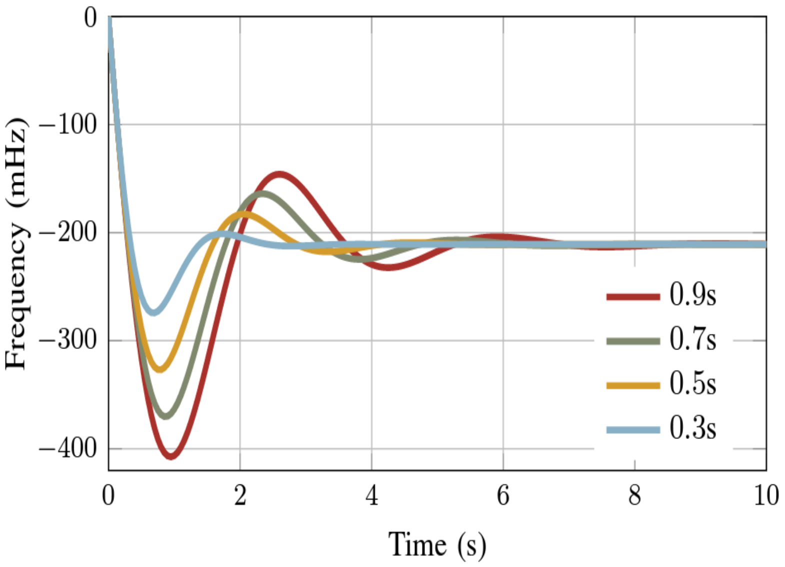
GFM Grid-shaping Through Lines [LCSS 23]

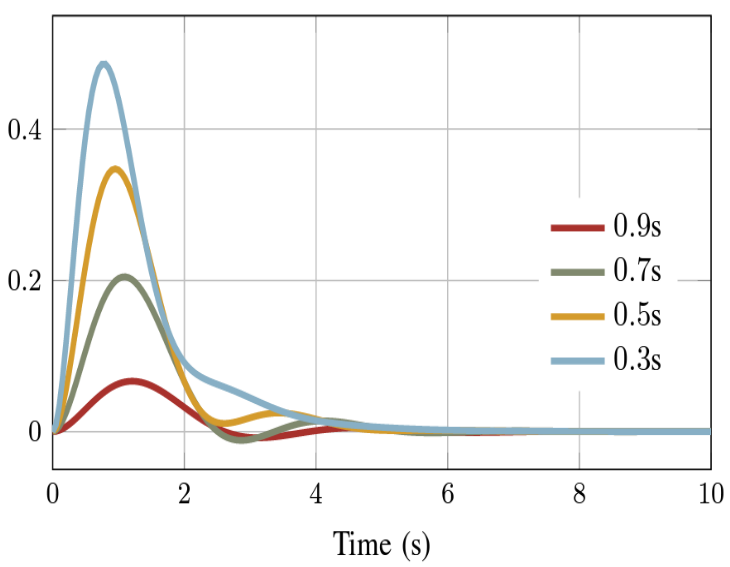
B. K. Poolla Y. Lin A. Bernstein D. Groß







Frequency response for a 1 p.u. load step



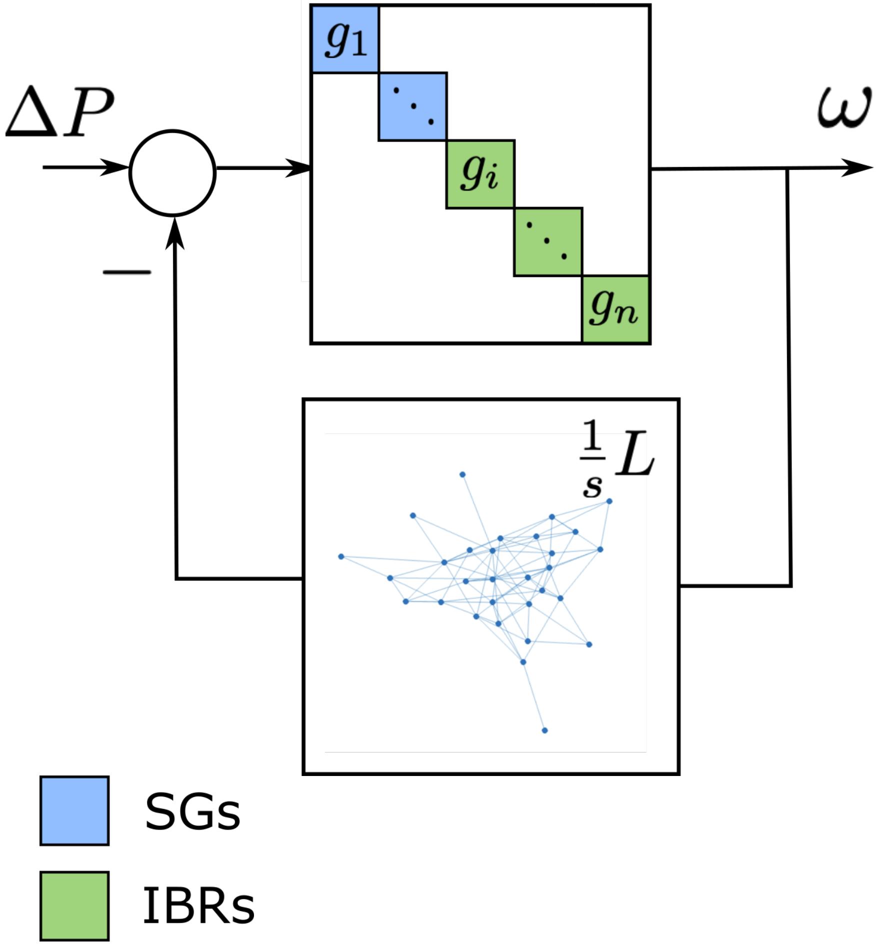
IBR power injection for a 1 p.u. load step

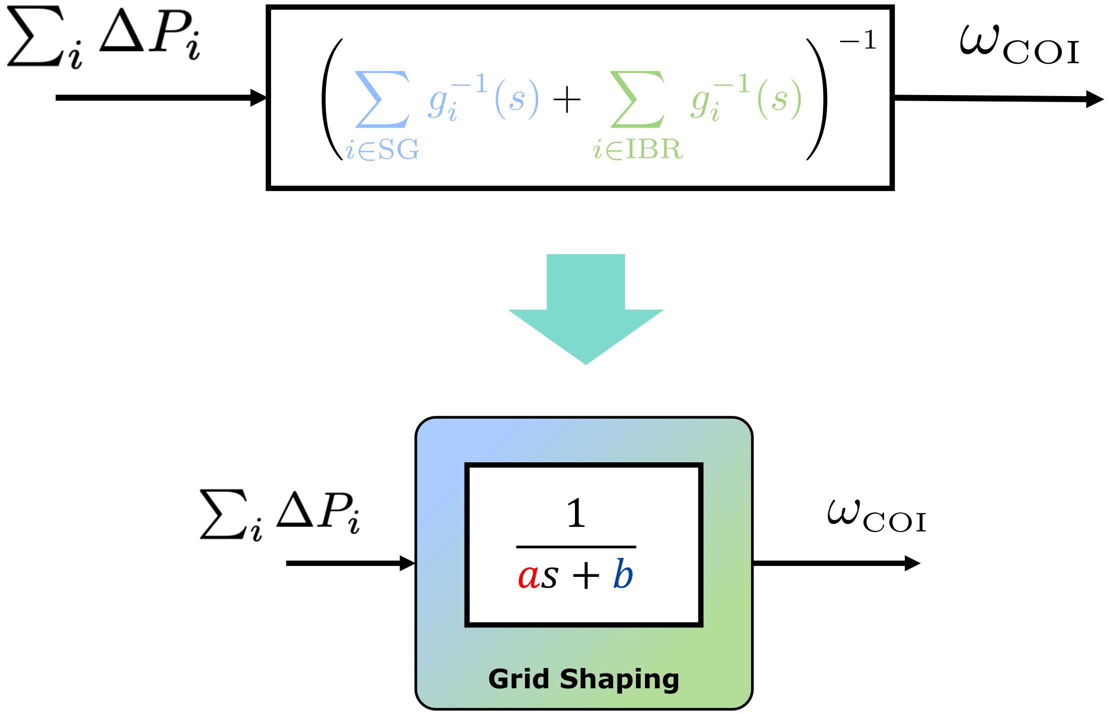
Tunable Performance:

E.g.: Turbine Time Constant = τ'

[LCSS 23] Poolla, Lin, Bernstein, M, Groß. Frequency shaping control for weakly-coupled grid-forming IBRs **IEEE Control Systems Letters 2023**

GFM System-wide Grid-shaping [LCSS 20]

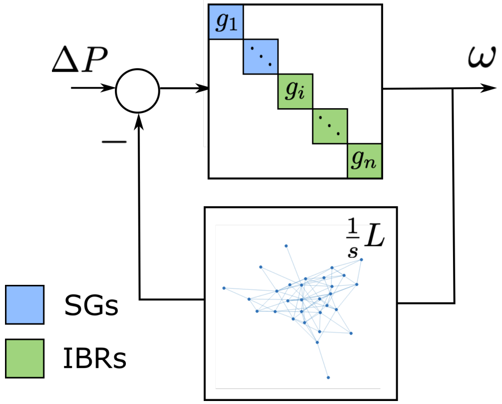


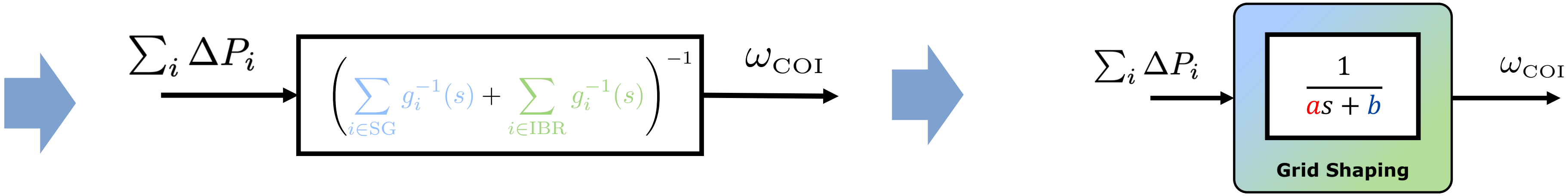


Tunable Performance: RoCoF $= \frac{1}{a}\Delta P, \ \Delta\omega = \frac{1}{b}\Delta P$

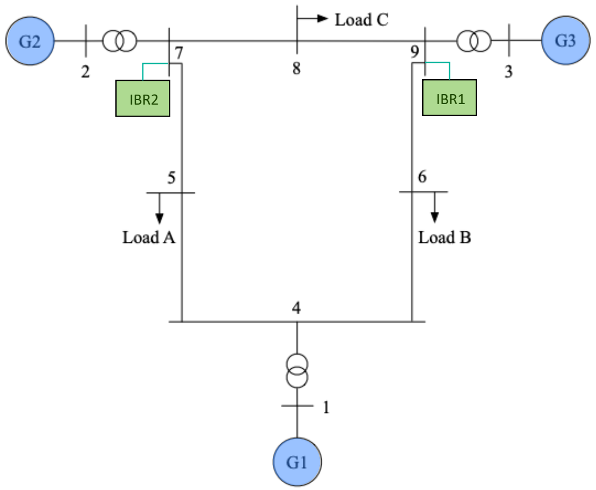
[LCSS 20] Jiang, Bernstein, Vorobev, M. Grid-forming frequency shaping control for low-inertia power systems **IEEE Control Systems Letters 2020**

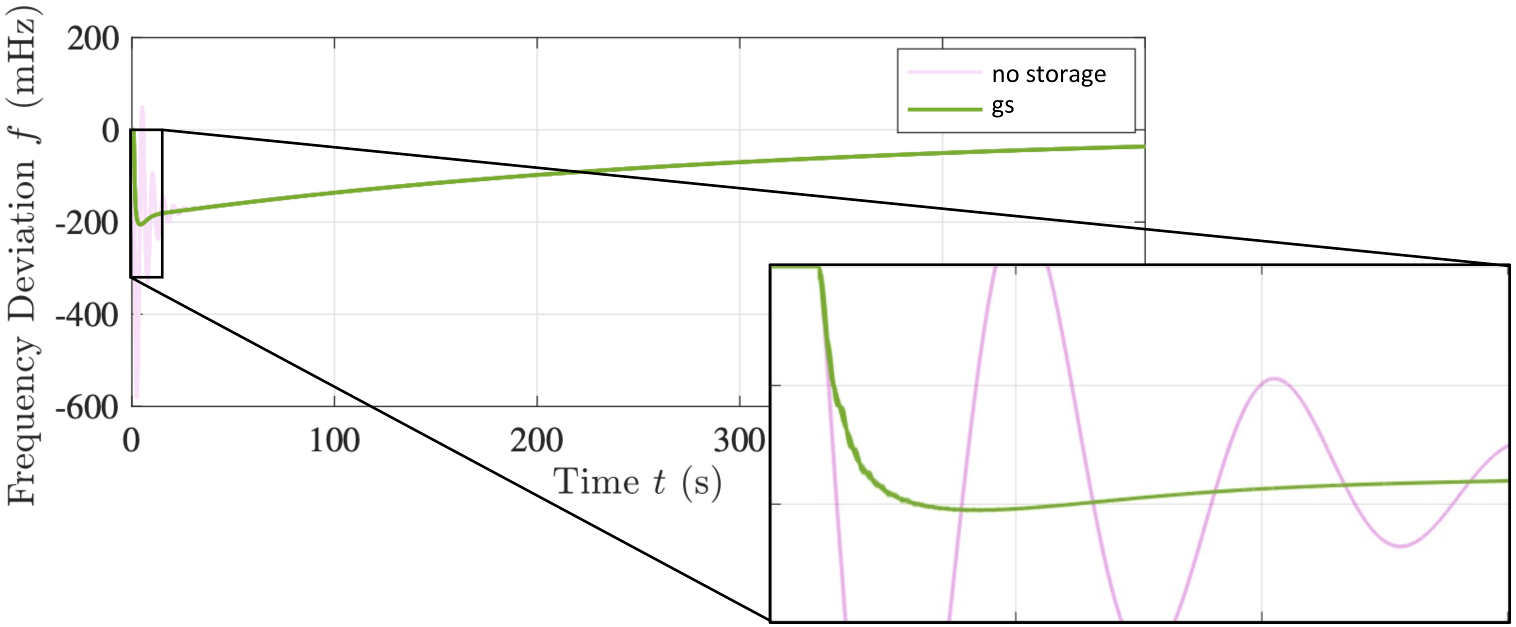
GFM System-wide Grid-shaping [LCSS 20]





Tunable Performance: RoCoF $= \frac{1}{a}\Delta P,\ \Delta\omega = \frac{1}{b}\Delta P$



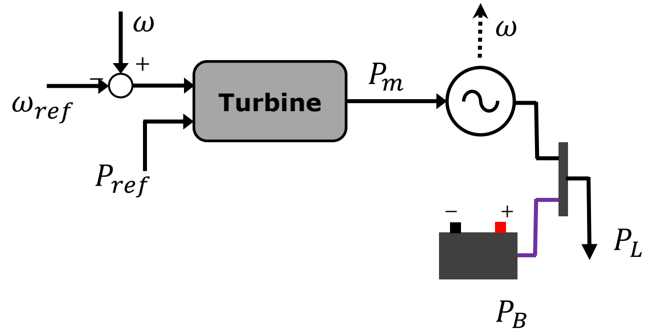


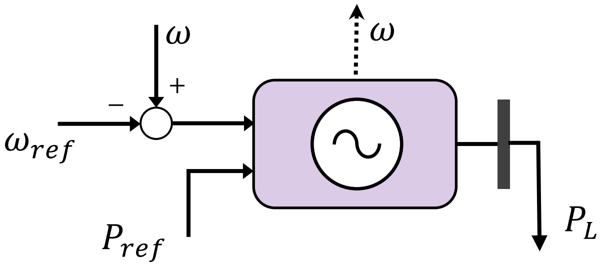
[LCSS 20] Jiang, Bernstein, Vorobev, M. Grid-forming frequency shaping control for low-inertia power systems **IEEE Control Systems Letters 2020**

Grid Shaping Control

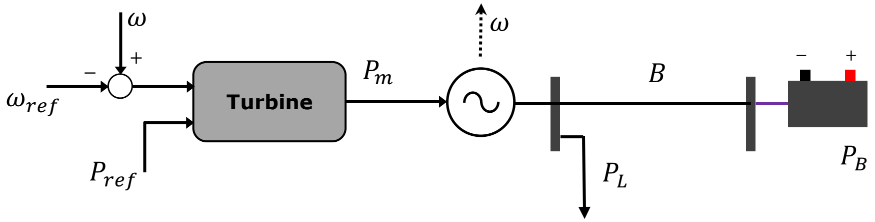
Use model matching control to shape system response

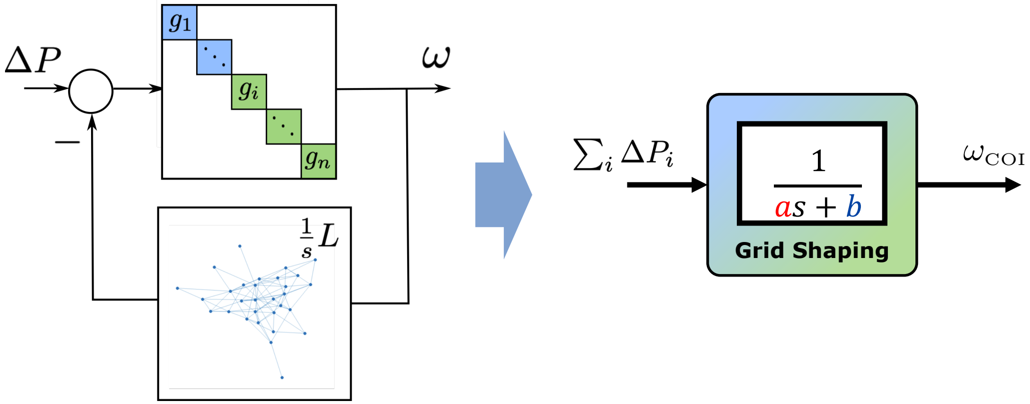
Grid-following IBRs





Grid-forming IBRs





Tunable Performance: RoCoF $= \frac{1}{a}\Delta P,\ \Delta\omega = \frac{1}{b}\Delta P,\ \tau', \ldots$

Summary

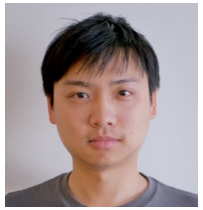
- **Merits and trade-offs of low inertia**
  - Control Perspective: Lighter systems are easier to control!
  - Smarter controller can provide multiple benefits in Nadir, RoCoF, inter-area oscillations, and disturbance rejection, with less effort

- **Analysis of Weakly-Connected Coherent Networks**
  - Generalized Center of Inertia captures IBR dynamics
  - Provide a new tunable target to meet system specs
  - Coherent modes identified via spectral clustering

- **Grid Shaping Control**
  - Grid-following/forming control framework for future girds
  - Leverages IBRs to *shape* the coherent response

Thanks!


Yan Jiang


Hancheng Min

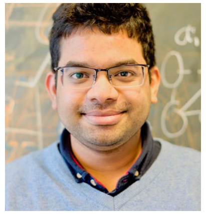

Eliza Cohn

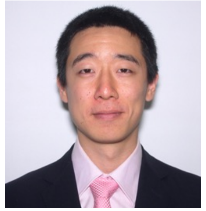

Petr Vorobev


Richard Pates


Fernando Paganini


Dominic Groß


Bala K. Poolla


Yashen Lin


Andrey Bernstein

Merits and trade-offs of low inertia

[TAC 21] Jiang, Pates, M, *Dynamic droop control in low inertia power systems*, **IEEE Transactions on Automatic Control, 2021**

Analysis of Weakly-Connected Coherent Networks

[CDC 19] Min, M. Dynamics concentration of large-scale tightly-connected networks. **Conference on Decision and Control 2019**

[LCSS 20] Min, Paganini, M. Accurate reduced-order models for heterogeneous coherent generators. **IEEE Control Systems Letters 2020**

[L4DC 23] Min, M. Learning coherent clusters in weakly-connected network systems. **Leaning for Dynamics and Control 2023**

[ArXiv 23] Min, Pates, M. A frequency domain analysis of slow coherency in networked systems. **arXiv:2302.08438 2023**, **submitted**

Grid Shaping Control

[LCSS 20] Jiang, Bernstein, Vorobev, M. Grid-forming frequency shaping control for low-inertia power systems **IEEE Control Systems Letters 2020**

[TPS 21] Jiang, Cohn, Vorobev, M. Storage-based frequency shaping control **Transactions on Power Systems 2021**

[LCSS 23] Poolla, Lin, Bernstein, M, Groß. Frequency shaping control for weakly-coupled grid-forming IBRs **IEEE Control Systems Letters 2023**

mallada@jhu.edu • Enrique Mallada • http://mallada.ece.jhu.edu

Backup Slides

Network Coherence: Heterogeneous Case

$$T(s) = \frac{1}{n}\bar{g}(s)\mathbb{1}\mathbb{1}^T + \boxed{T(s) - \frac{1}{n}\bar{g}(s)\mathbb{1}\mathbb{1}^T} \qquad \bar{g}(s) = \left(\frac{1}{n}\sum_{i=1}^{n} g_i^{-1}(s)\right)^{-1}$$

The effect of non-coherent dynamics vanishes as:

- For almost any $s_0 \in \mathbb{C}$

$$\lim_{\lambda_2(L)\to+\infty} \left\| T(s_0) - \frac{1}{n}\bar{g}(s_0)\mathbb{1}\mathbb{1}^T \right\| = 0$$

- For $s_0 \in \mathbb{C}$, a pole of $f(s)$

$$\lim_{s\to s_0} \left\| T(s) - \frac{1}{n}\bar{g}(s)\mathbb{1}\mathbb{1}^T \right\| = 0$$

- Excluding zeros: the limit holds at zero, but by different convergence result
- We can further prove **uniform convergence** over a compact subset of complex plane, if it doesn't contain any zero nor pole of $\bar{g}(s)$
- Extensions for random network ensembles, $g_i(s) := g(s, w_i)$ (w_i random), then $\bar{g}(s) = (E_w[\,g^{-1}(s,w)])^{-1}$
- Convergence of transfer matrix is **related to time-domain response** by Inverse Laplace Transform

Connection to Time Domain

If $\bar{g}(s)$ and $T(s)$ stable ($\left|\left|\bar{g}\right|\right|_\infty, \left|\left|T\right|\right|_\infty \leq \gamma$), then there is $\bar{\lambda} = O(\gamma/\varepsilon)$ such that:

- **ε-approximation,** for any network L, with $\lambda_2(L) \geq \bar{\lambda}$

$$\sup_{t>0} |y_i(t) - \bar{y}(t)| \leq \varepsilon$$

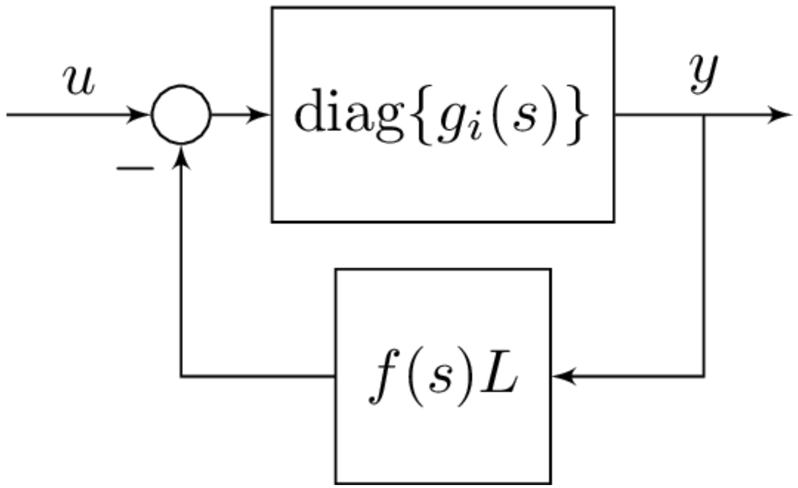
where $\bar{y}(t)$ is the coherence dynamics response: $y(s) = \bar{g}(s)\frac{1}{n}\sum_{i=1}^{n} u_i(s)$

- **element-wise coherence**, for any pair of nodes i and j

$$\sup_{t>0} |y_i(t) - y_j(t)| \leq 2\varepsilon$$

Example: Icelandic Power Grid

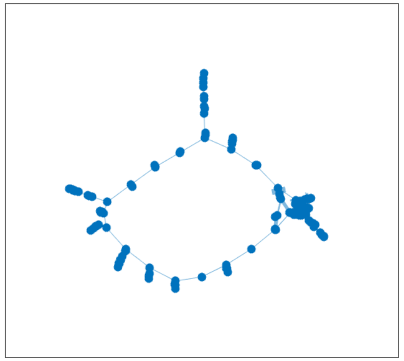
- Iceland power network: 189 buses, 35 generators, load 1.3GW (PSAT)



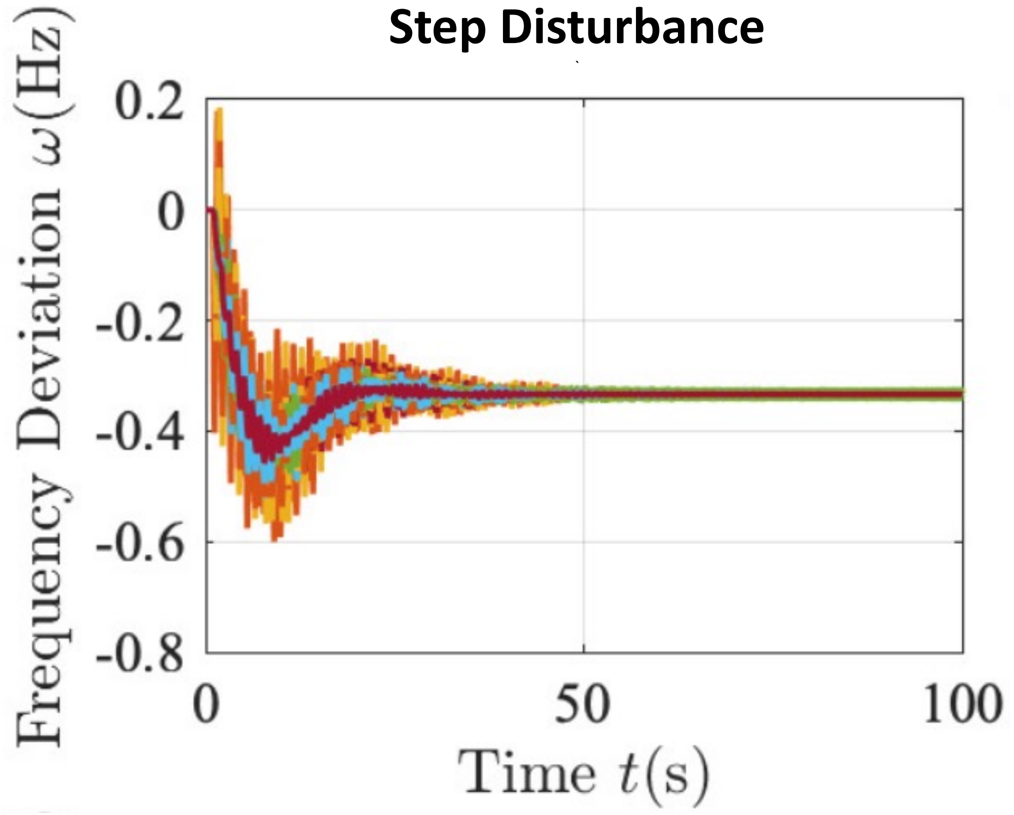
$$g_i(s) = \frac{1}{m_i s + d_i + \frac{r_i^{-1}}{\tau_i s + 1}}$$

$$f(s) = \frac{1}{s}$$

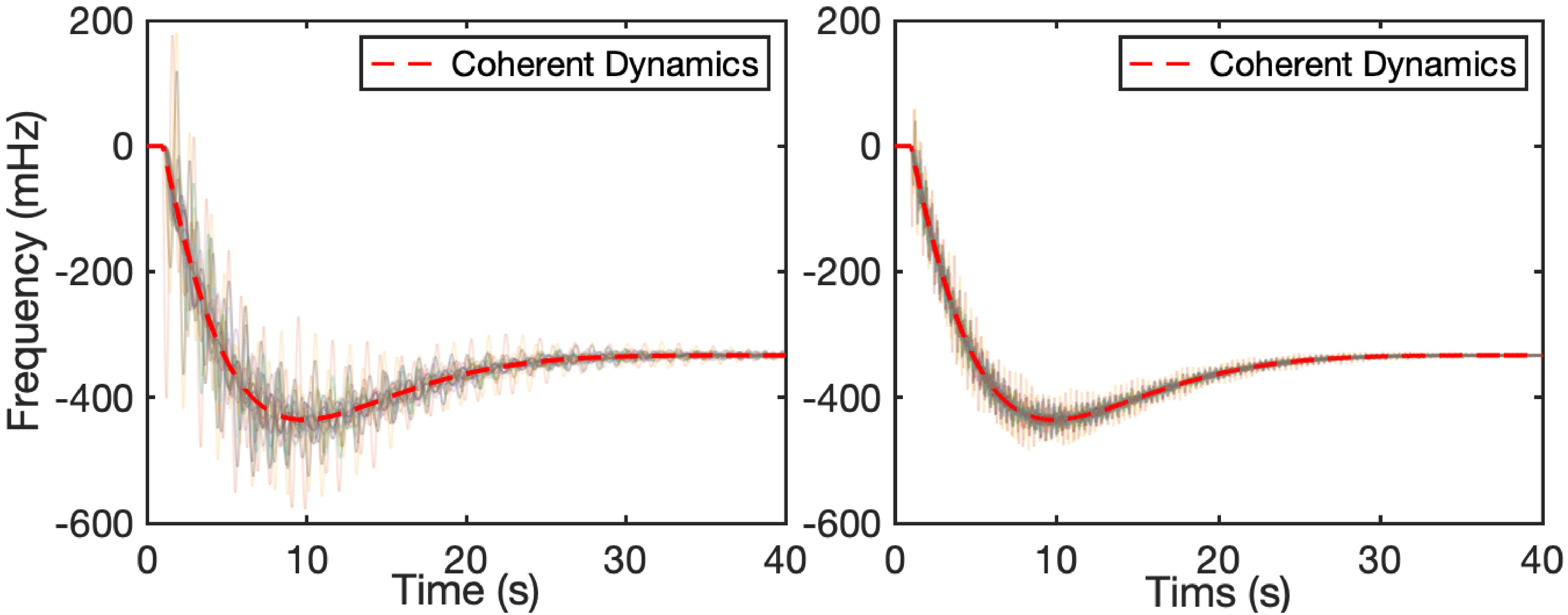
Icelandic Grid



Step Disturbance



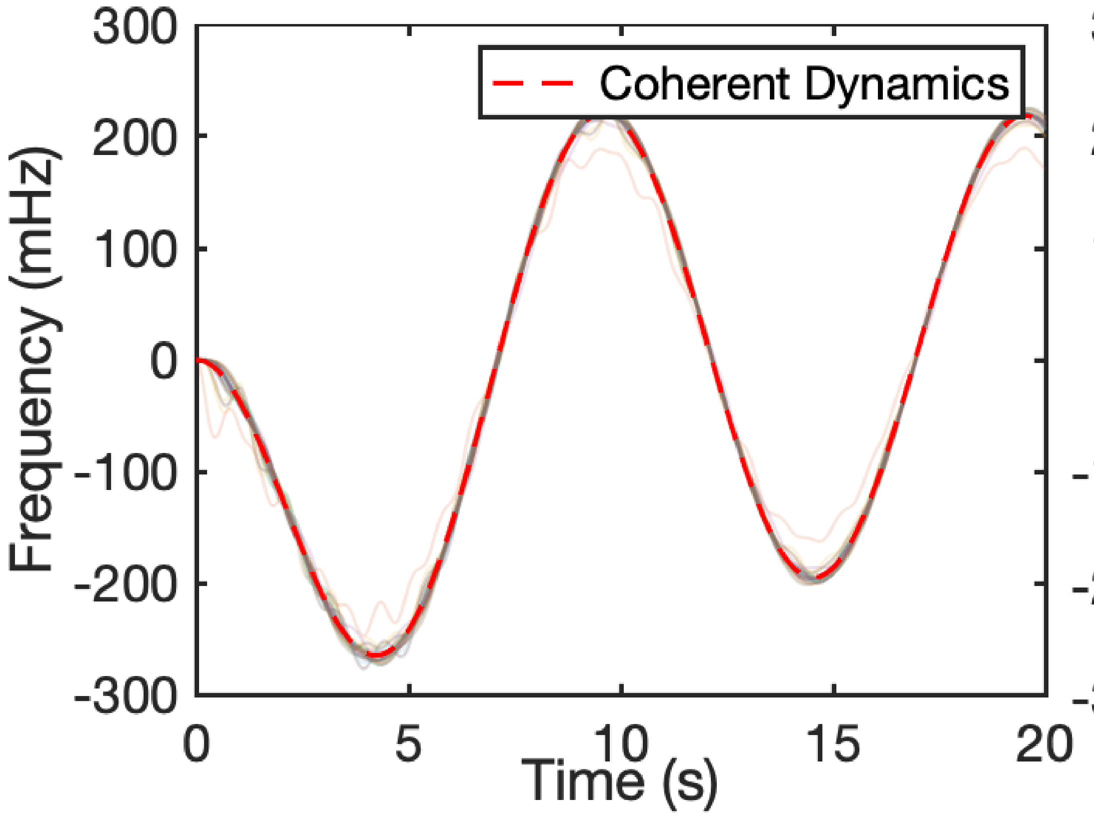
Example: Effect of Network Algebraic Connectivity $\lambda_2(L) \uparrow$

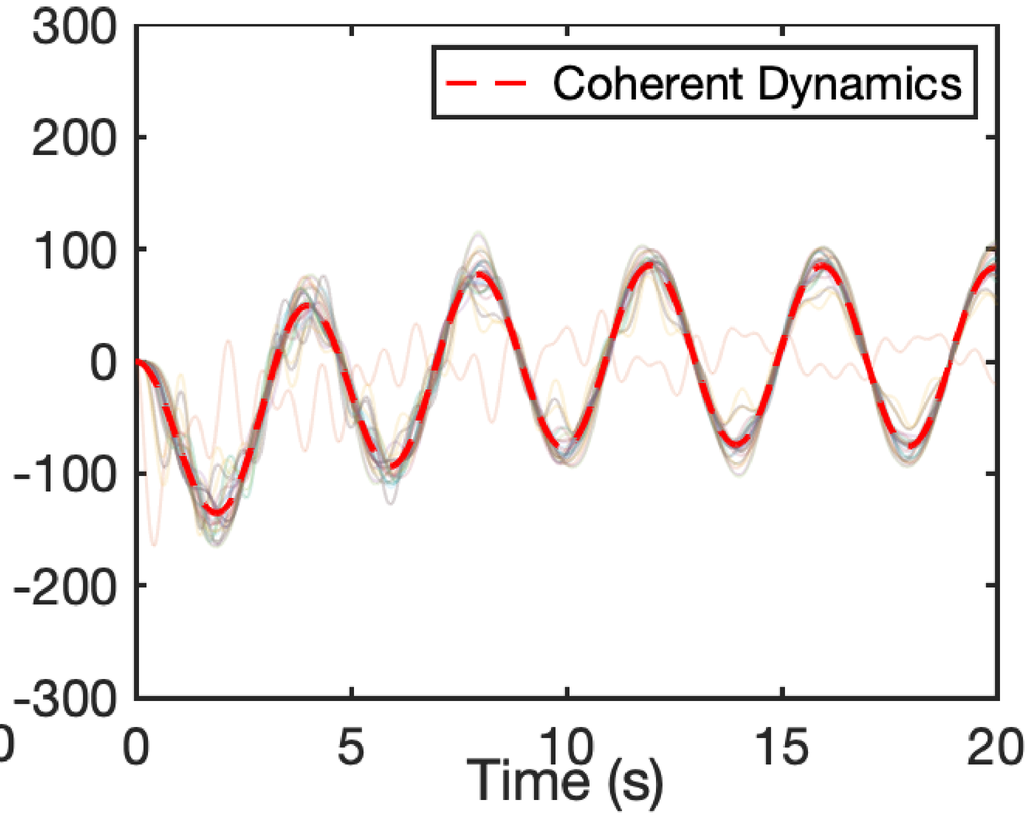


Coherent dynamics acts as a more accurate version of the Center of Inertia (CoI)

Example: Sinusoidal Disturbances: $\sin(\boldsymbol{\omega_d t})$

$\omega_d \uparrow$

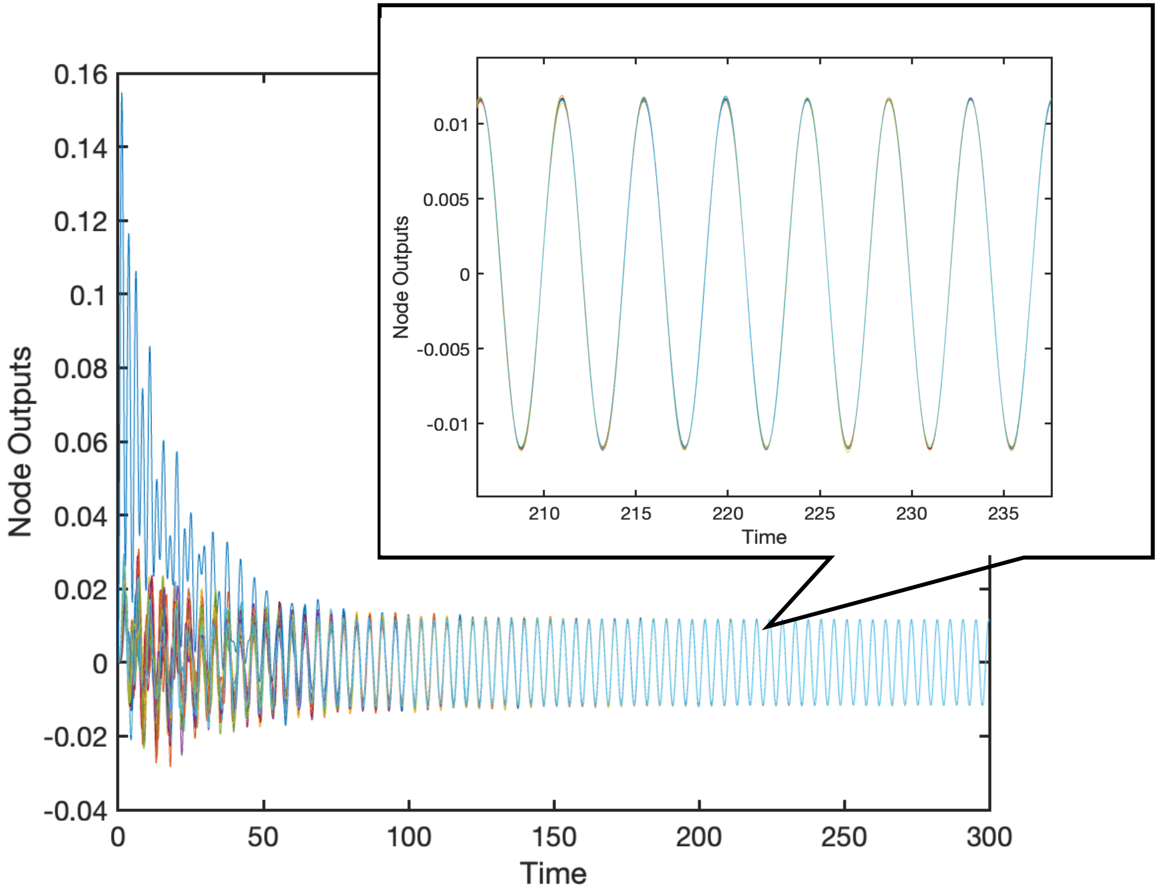




Frequency-dependent Coherence from Coupling Dynamics

- Frequency dependent coherence:
  A stable network responds coherently when subject to signal with its frequency component concentrated around pole of $f(s)$

- An Artificial Example:
  A stable heterogenous network with $f(s) = \frac{s}{s^2+\omega_0^2}$ is "synchronized" by external sinusoidal input $\sin \omega_0 t$
  (Such coherence is robust to small changes in input frequency)



First order nodal dynamics $g_i(s) = \frac{1}{m_i s+d_i}$

20 nodes with $m_i \sim Unif(1,5), d_i \sim Unif(0.1, 0.5)$

12-regular graph with unit weights

Sin input to the first node(shown in blue) only