Grid Shaping Control for High-IBR Power Systems

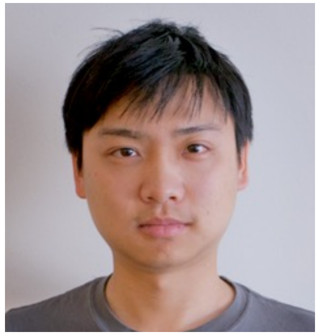
Enrique Mallada, Johns Hopkins

Panel on *Future electricity systems: How to handle millions of power electronic-based devices and other emerging technologies*

Acknowledgements

Students

Yan Jiang



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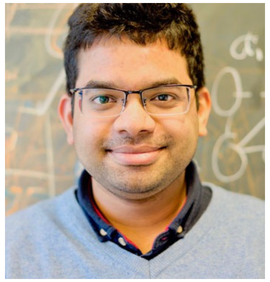
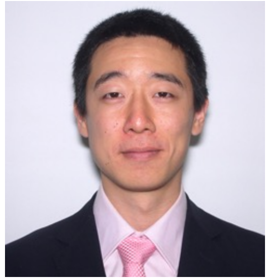


Bala K. Poolla



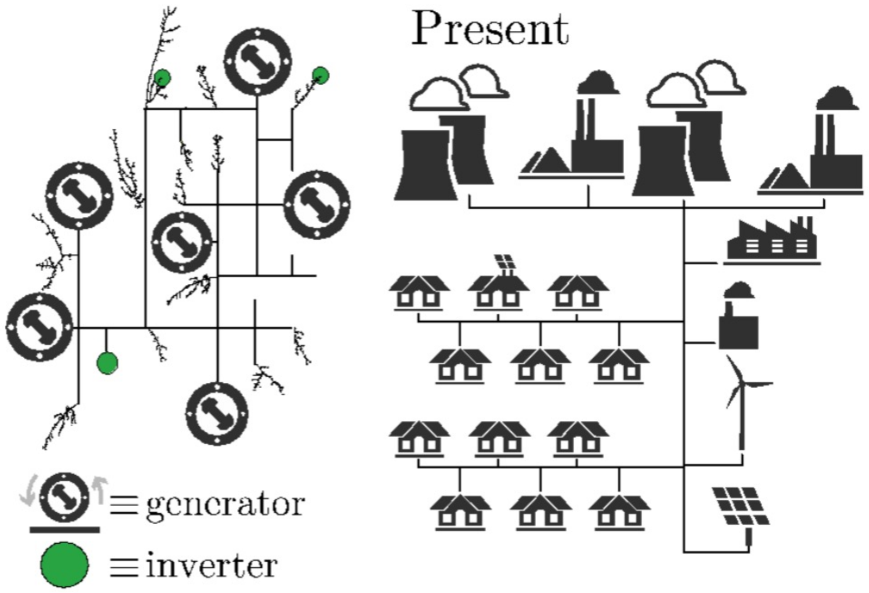
Yashen Lin

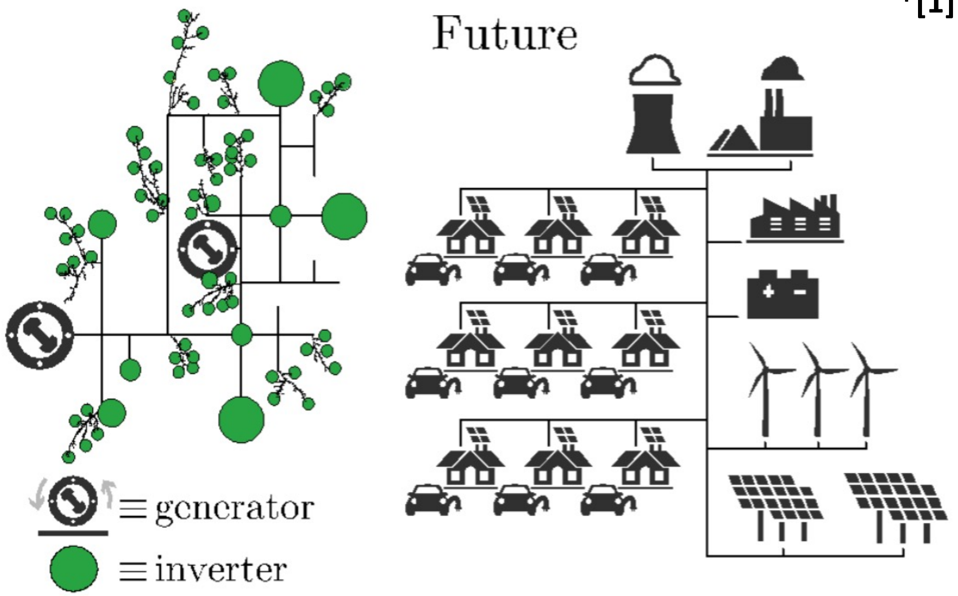
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Andrey Bernstein

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)

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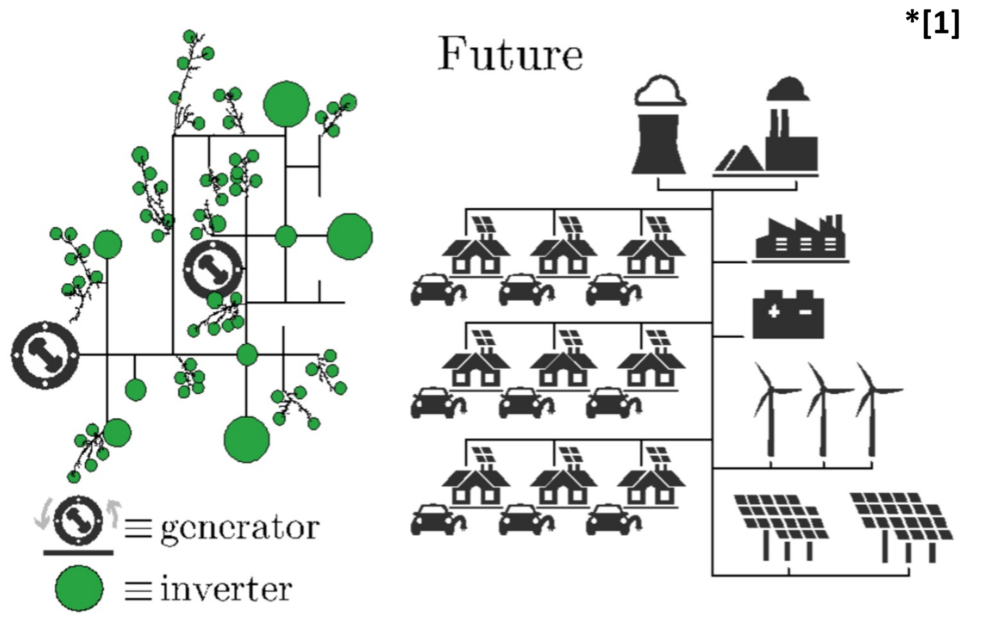
[1] Lin et al. Research roadmap on grid-forming inverters. Technical report, National Renewable Energy Lab.(NREL), Golden CO, 2020

The Future Grid



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 the limited number of SGs remaining

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?

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

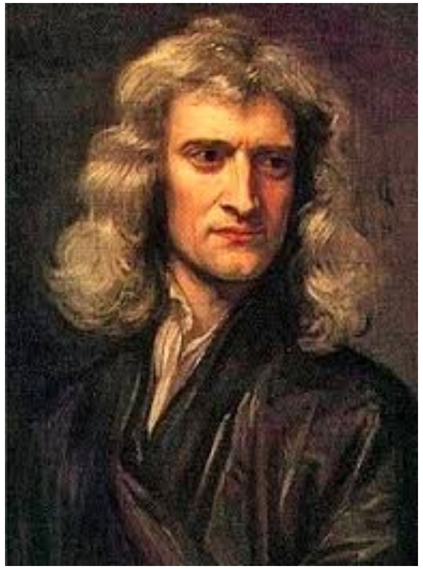
Outline

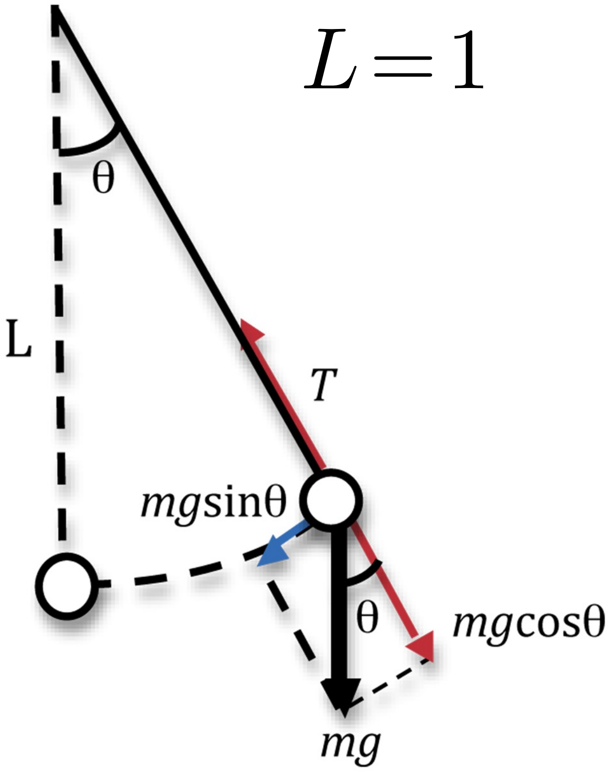
- Merits and trade-offs of low inertia
    - Control Perspective: Lighter systems are easier to control!

- Analysis of IBR-rich Coherent Networks
    - Generalized Center of Inertia captures IBR dynamics

- Grid Shaping Control
    - Grid-following/forming control framework for future girds

Merits and Trade-offs of Inertia





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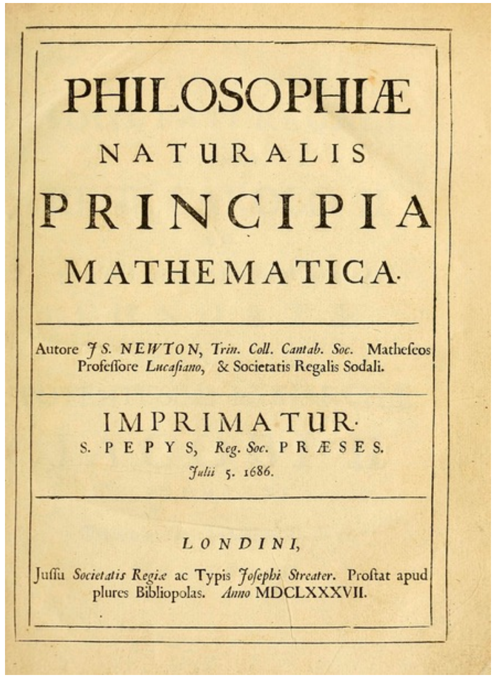

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S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

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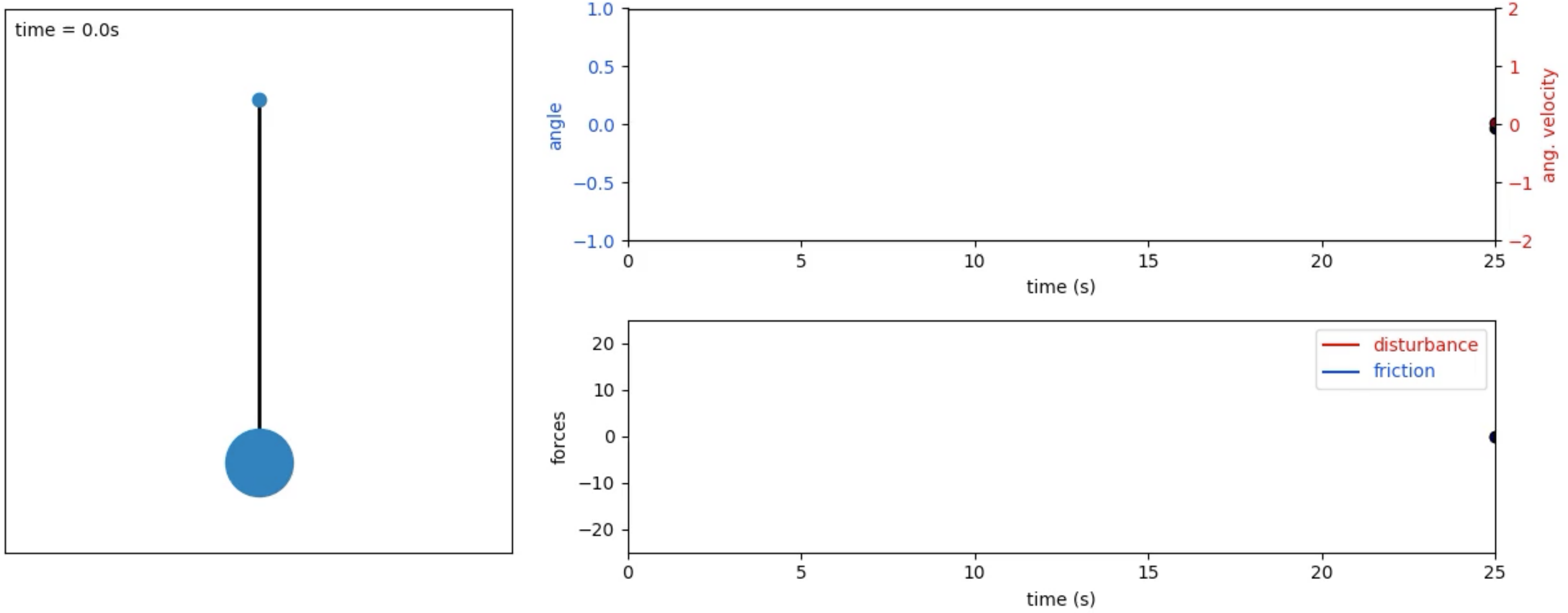
plures Bibliopolas. *Anno* MDCLXXXVII.

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

Merits and Trade-offs of Inertia

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

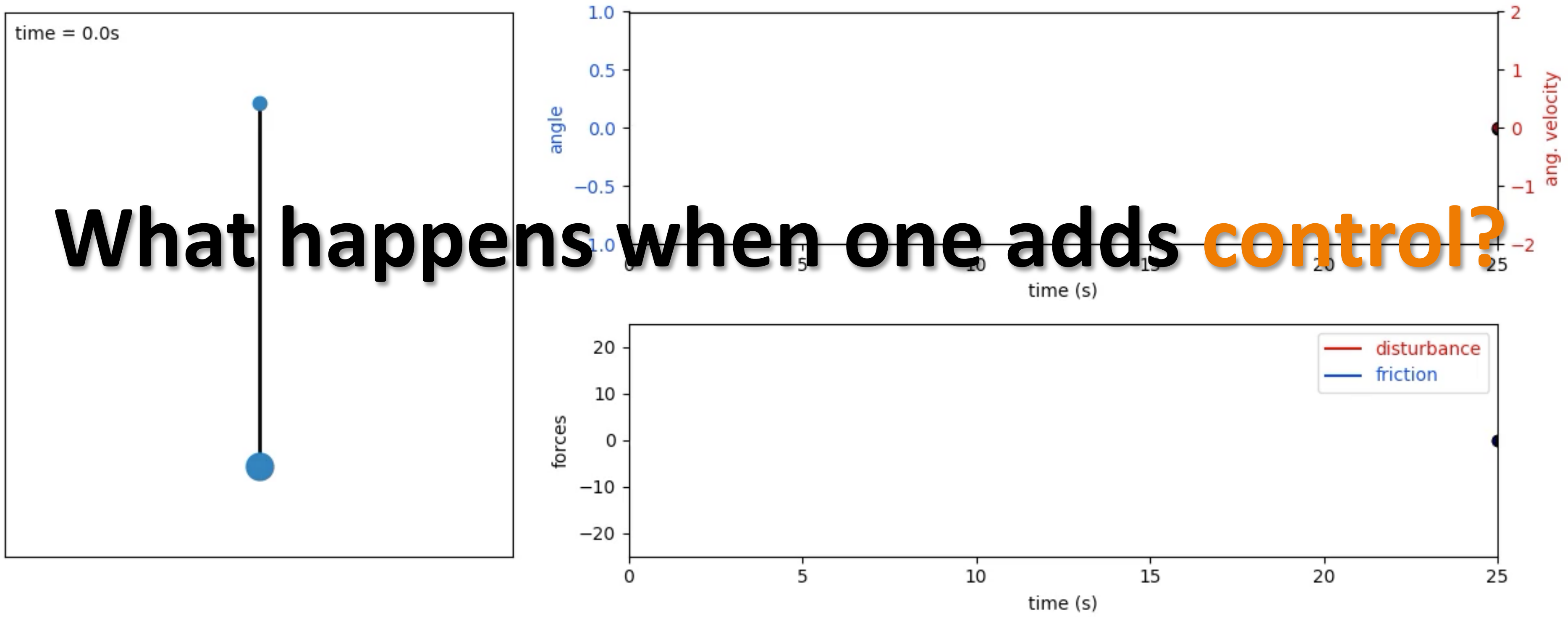


Pros: Provides natural disturbance rejection

Cons: Hard to regain steady-state

Merits and Trade-offs of Low Inertia

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



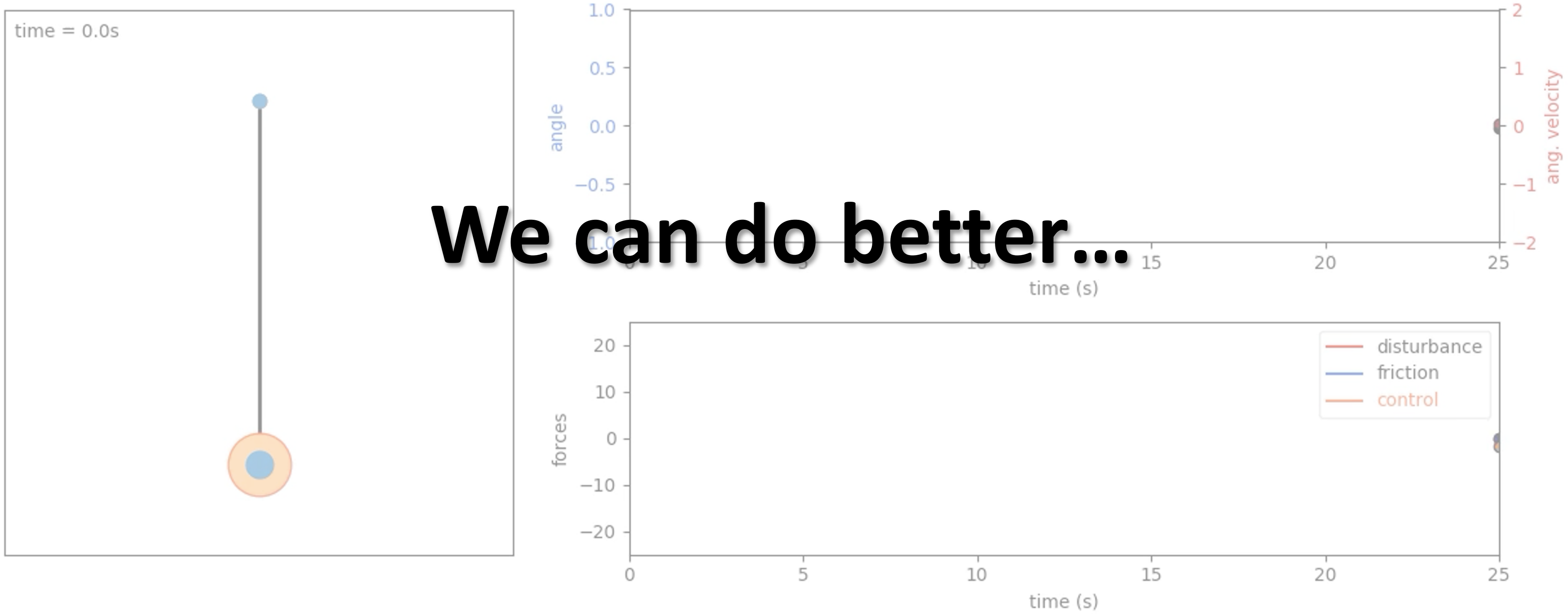
What happens when one adds control?

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…

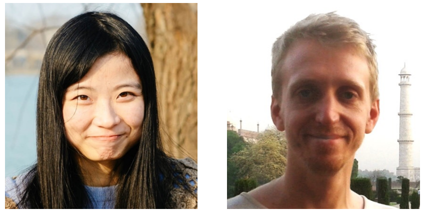
Pros:

Provides disturbance rejection

Cons:

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

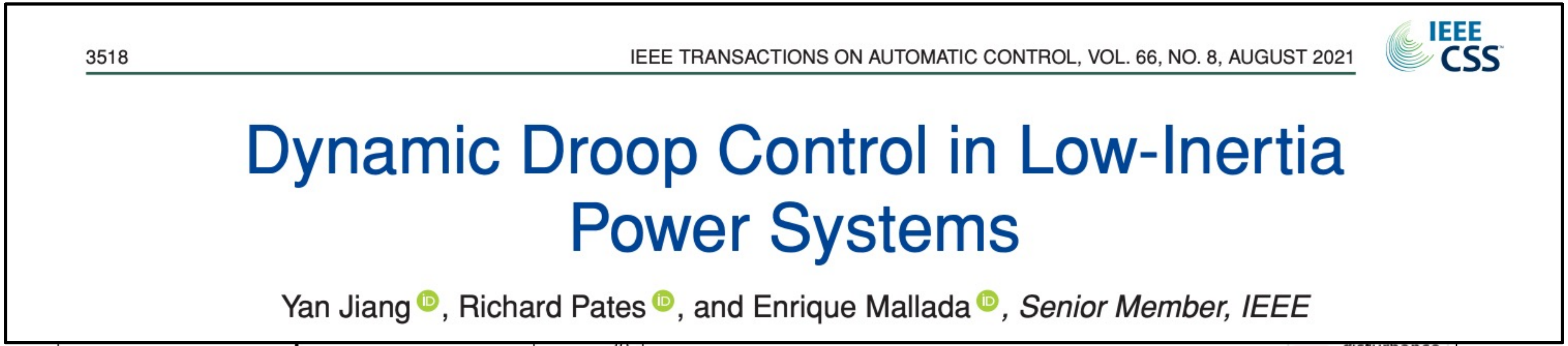
Control of Low Inertia Pendulum


Yan Jiang Richard Pates

Dynamic Droop:

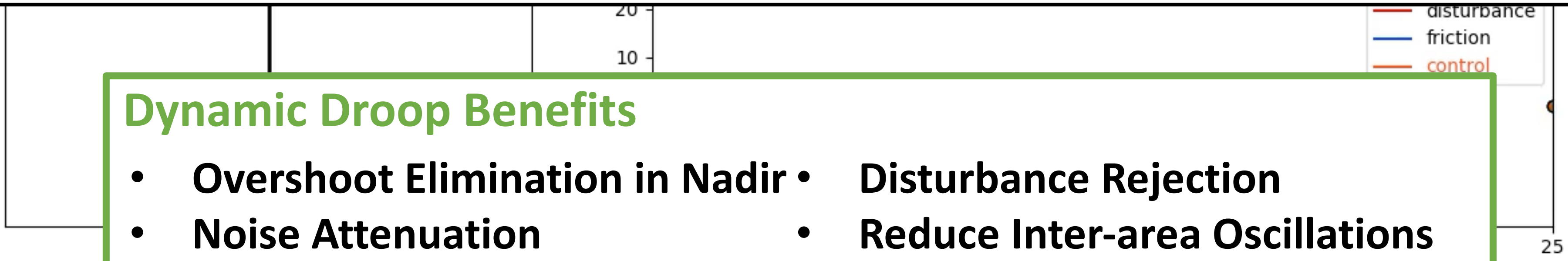
$$m\ddot{\theta} = -d\dot{\theta} - mg\sin\theta + f + x$$

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


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**
- **Disturbance Rejection**
- **Noise Attenuation**
- **Reduce Inter-area Oscillations**

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

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Coherence in Power Systems

Studied since the 70s

- Podmore, Price, Chow, Kokotovic, Verghese, Pai, Schweppe,…

Enables aggregation/model reduction

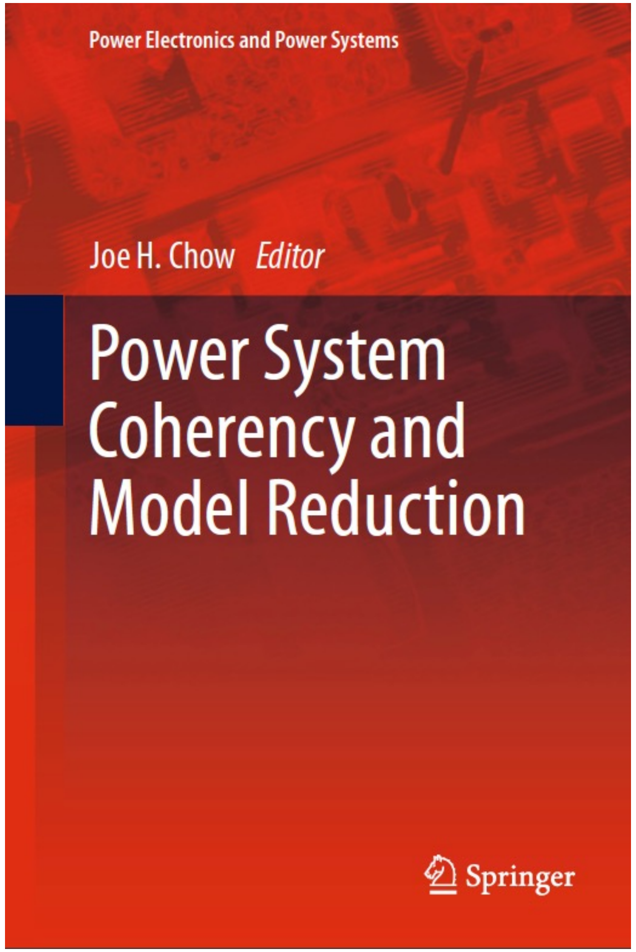
- Speed up transient stability analysis

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)



Power Electronics and Power Systems

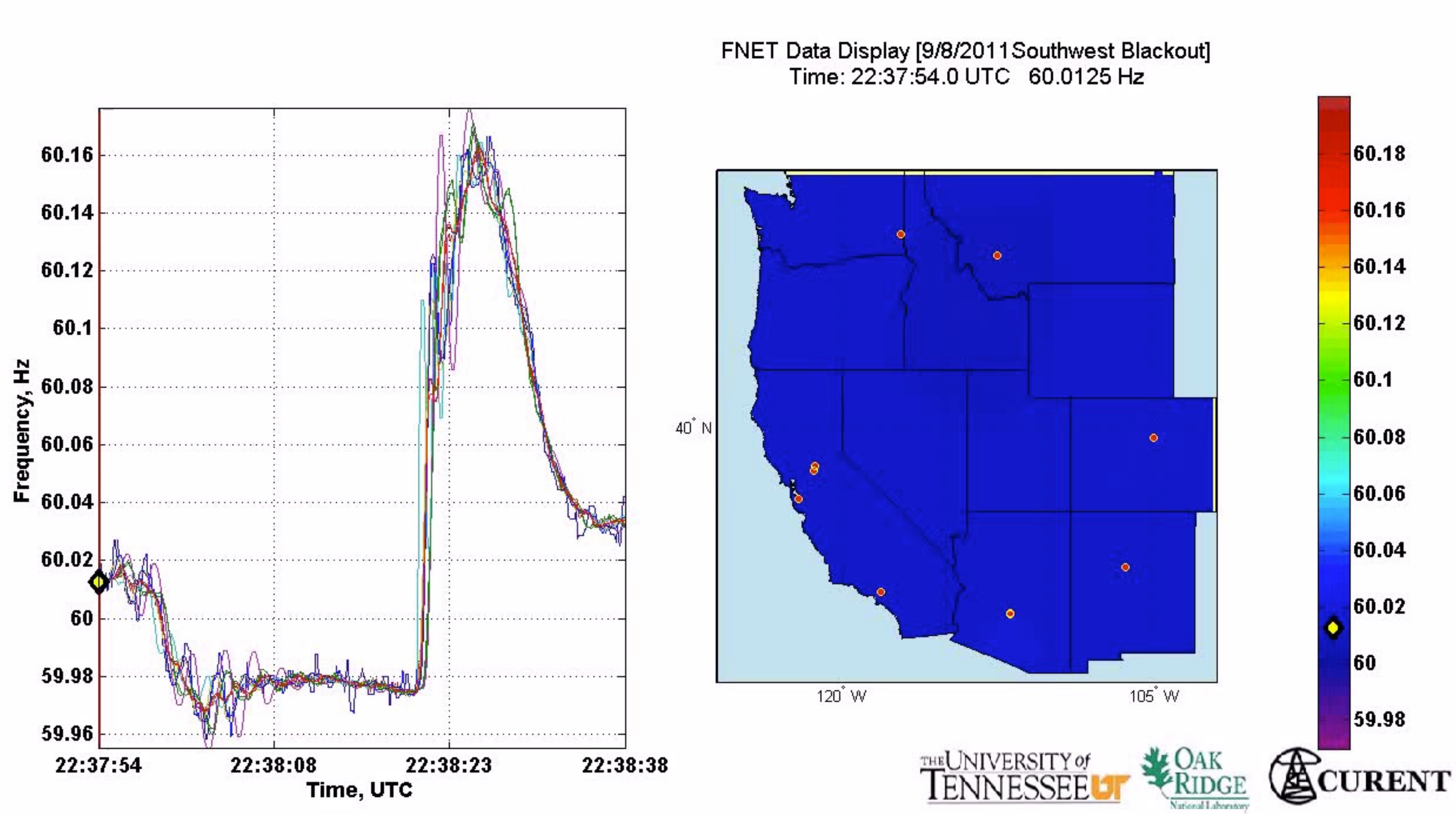
Joe H. Chow *Editor*

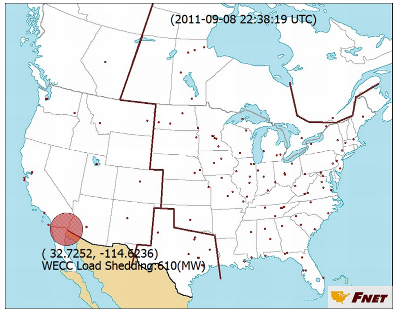
Power System Coherency and Model Reduction

Springer

Question: What is the role of IBRs in determining the coherent response?

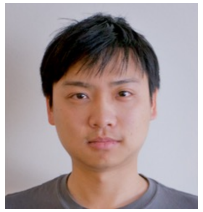
Coherence in Power Systems



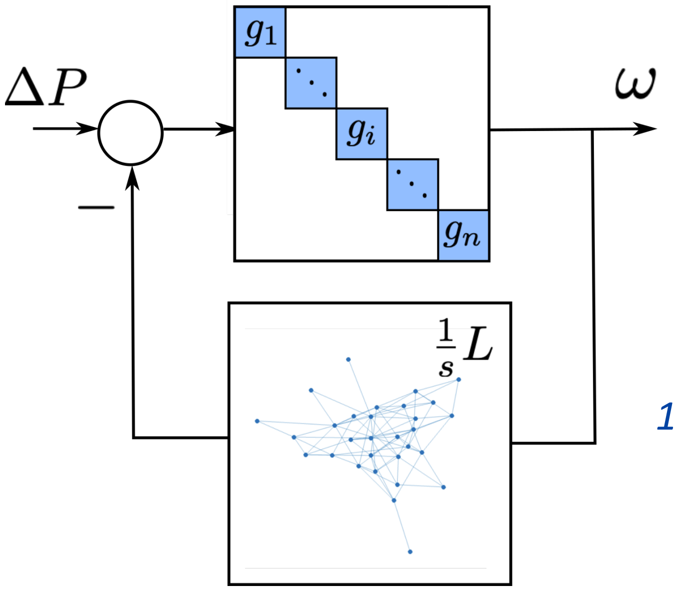


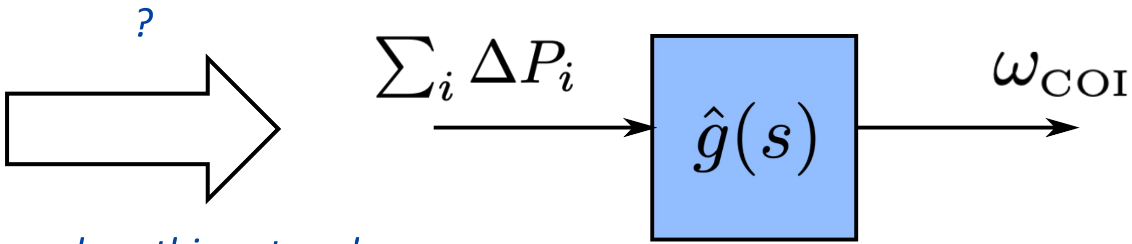
System response: Is affected by SG dynamics, network, disturbances,…

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?*

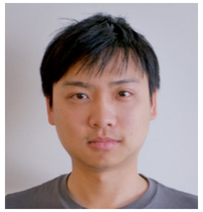
Problem Setup:

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

[CDC 19] Min, M. Dynamics concentration of large-scale tightly-connected networks. **CDC 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]



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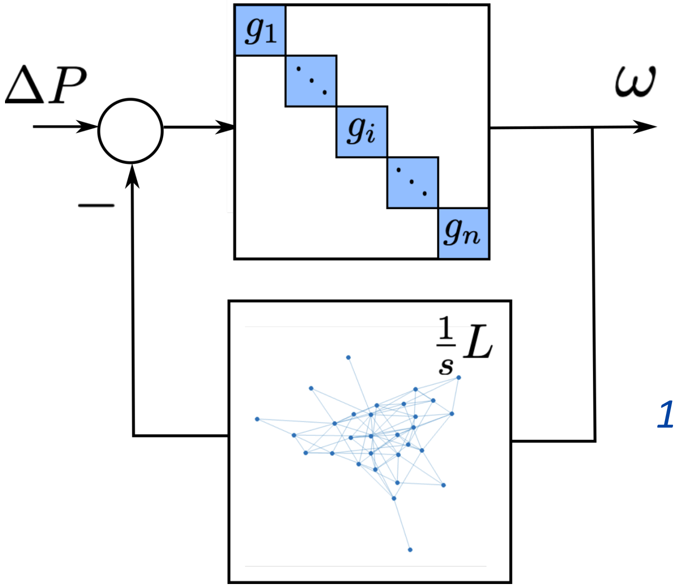

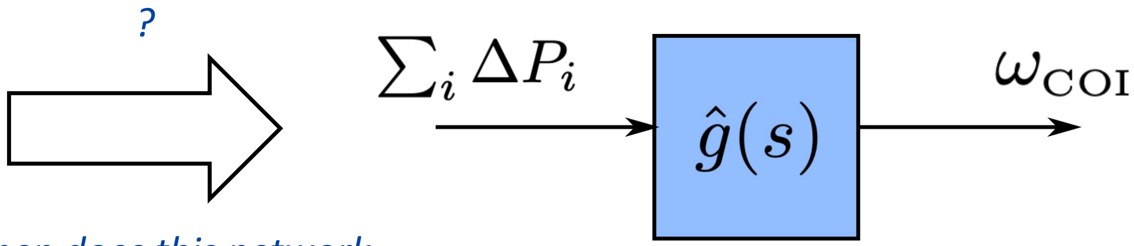

1.When does this network exhibit coherence?

*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** $\left|\frac{1}{s_0}\lambda_2\right|$ 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. **CDC 2019**

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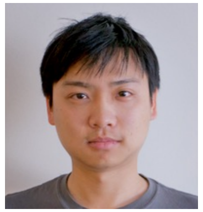
Generalized Center of Inertia [CDC 19,ArXiv 23]



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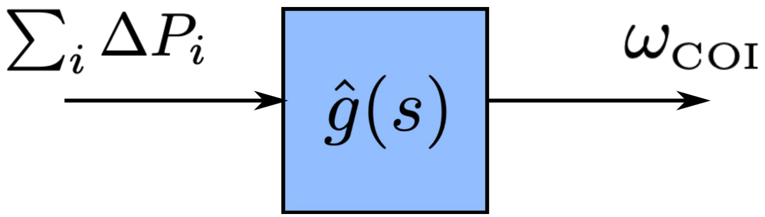
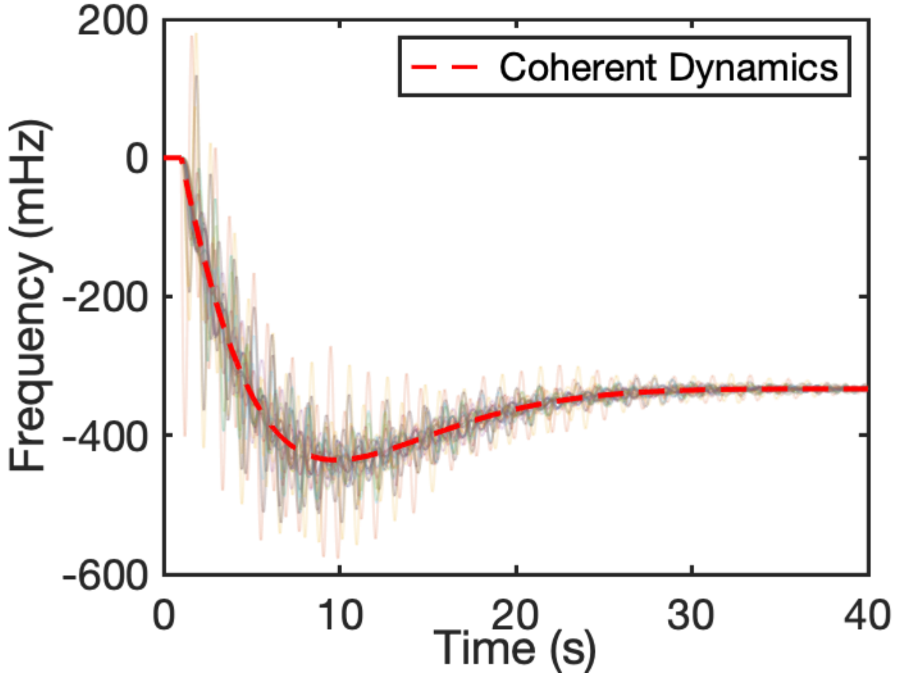




$$\hat{g}(s) = \left(\sum_{i=1}^{n} g_i^{-1}(s)\right)^{-1}$$

Coherent Dynamics: $\hat{g}(s)$

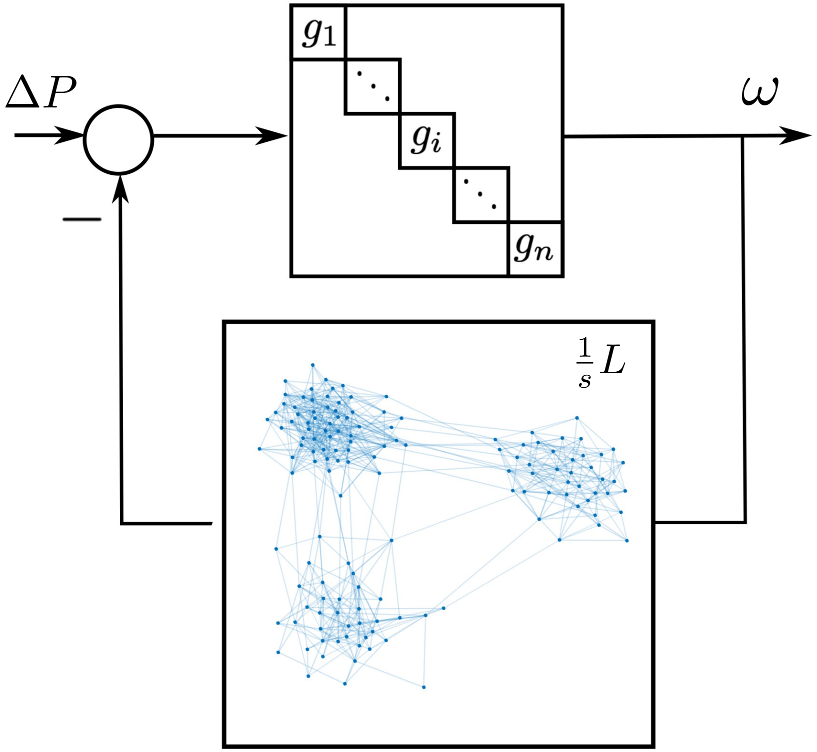
- Representation of aggregate response
- Accuracy of approximation:
  - is frequency dependent
  - increases with network connectivity
- Provides excellent template for reduced order models (via balance-truncations)
- More details [LCSS 20]

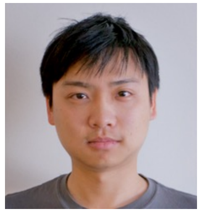
[CDC 19] Min, M. Dynamics concentration of large-scale tightly-connected networks. **CDC 2019**

[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 [L4DC 23]





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[L4DC 23] Min, M. Learning coherent clusters in weakly-connected network systems. **L4DC 2023**

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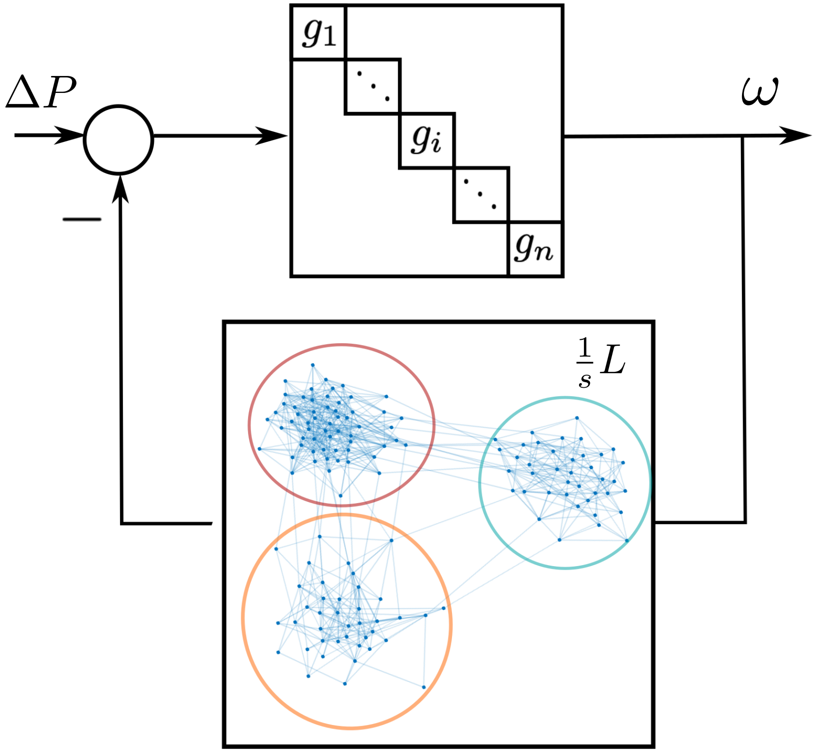
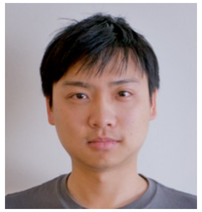




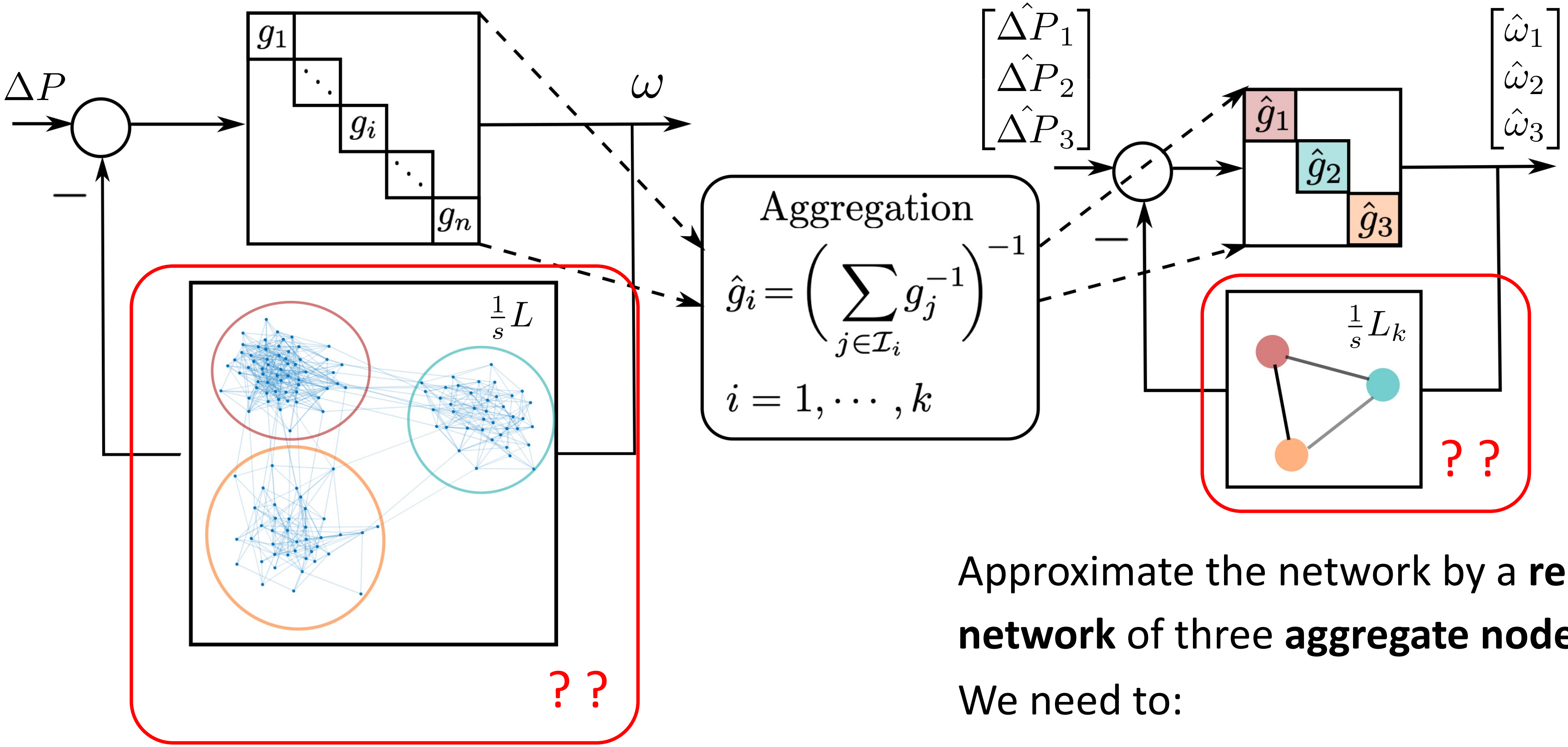
Hancheng Min

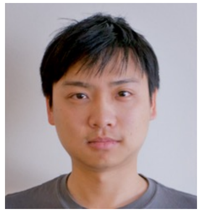
Three coherent groups:

- High intra-group connectivity
- Low inter-group connectivity

[L4DC 23] Min, M. Learning coherent clusters in weakly-connected network systems. **L4DC 2023**

Weakly-Connected Coherent Networks [L4DC 23]





Hancheng Min

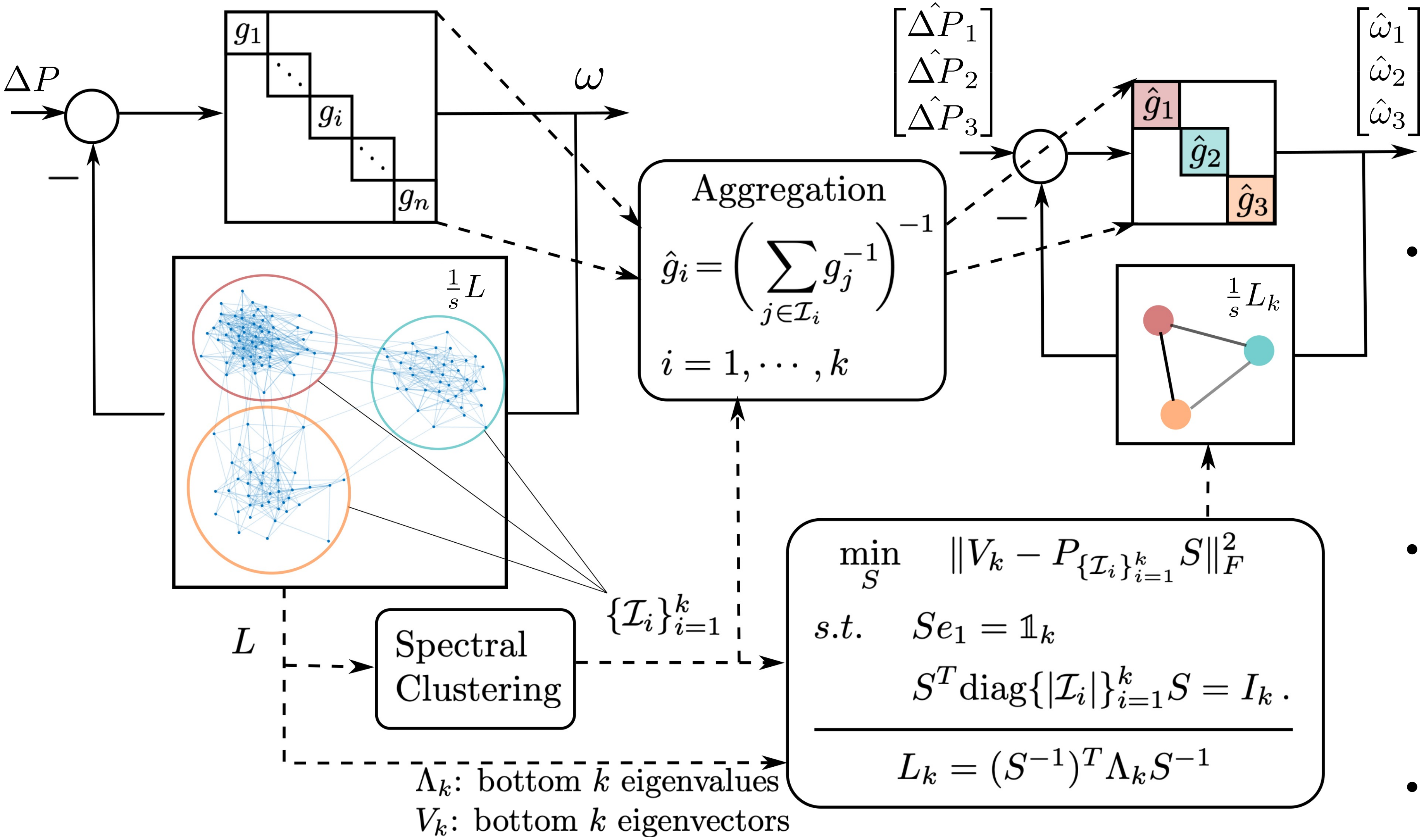
Approximate the network by a **reduced network** of three **aggregate nodes**

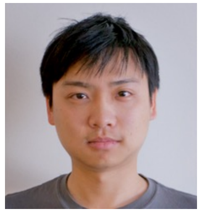
We need to:

- **Identify** the coherent groups
- Find the right **interconnection** for the reduced network

[L4DC 23] Min, M. Learning coherent clusters in weakly-connected network systems. **L4DC 2023**

Weakly-Connected Coherent Networks [L4DC 23]





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- **Spectral clustering** on graph Laplacian identifies coherent groups
- **Spectral embedding refinement** finds the interconnection
- **Structure-preserving** model reduction

[L4DC 23] Min, M. Learning coherent clusters in weakly-connected network systems. **L4DC 2023**

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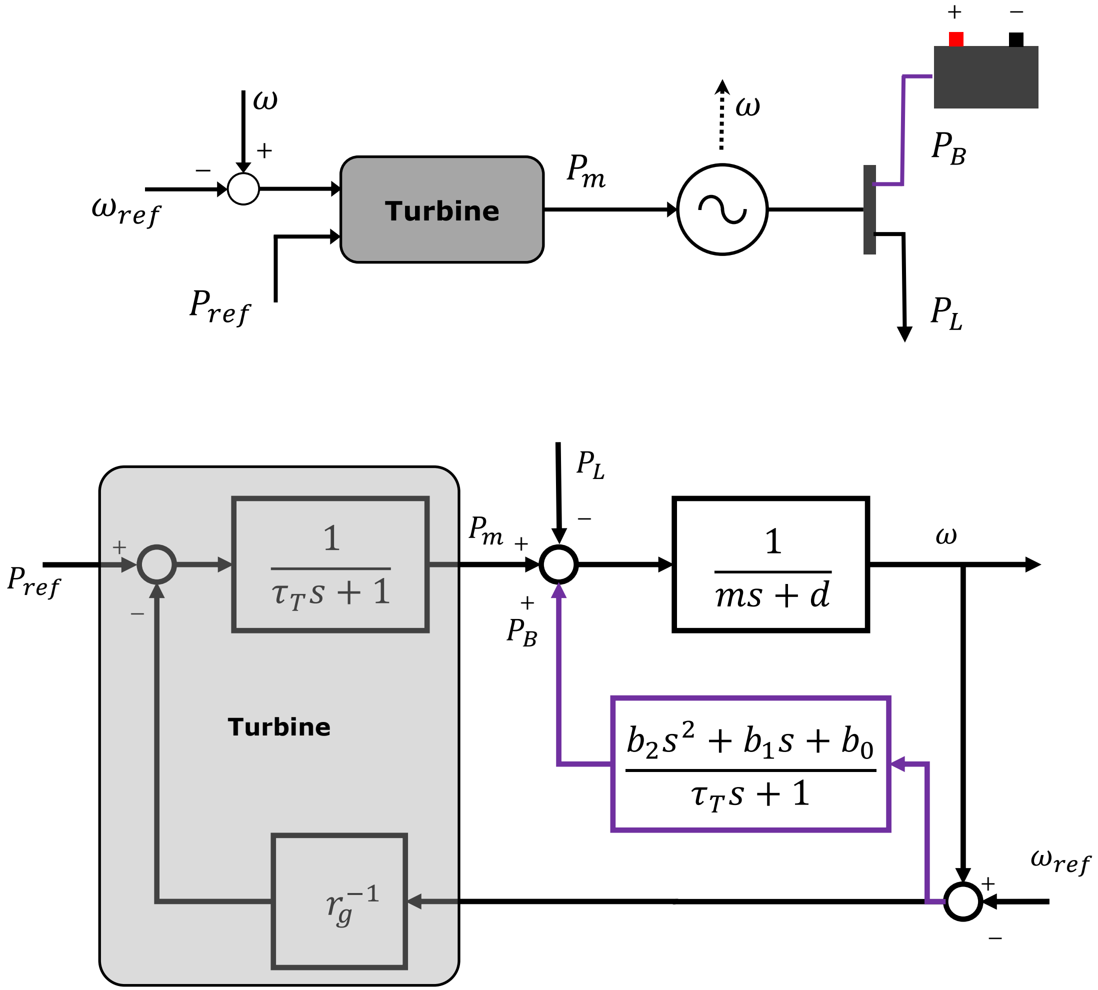
Grid Shaping Control

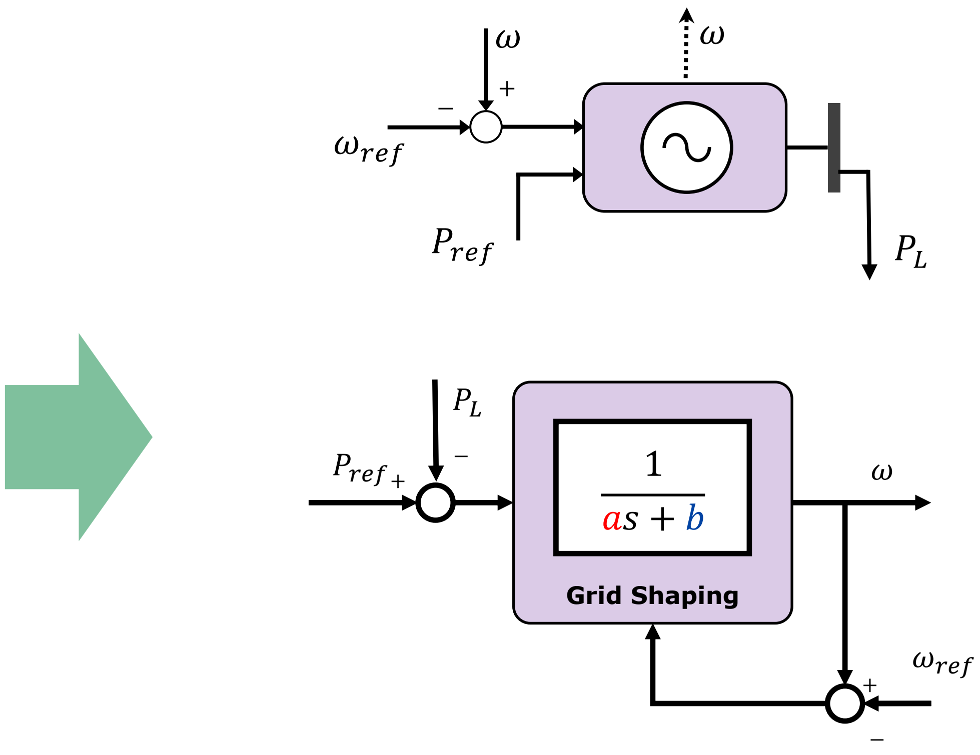
Use model matching control to shape SGs response

Grid-following IBRs

Grid-forming IBRs

Grid-shaping with GFL IBRs [TPS 21]



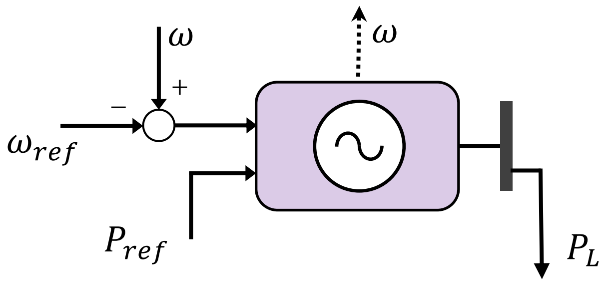


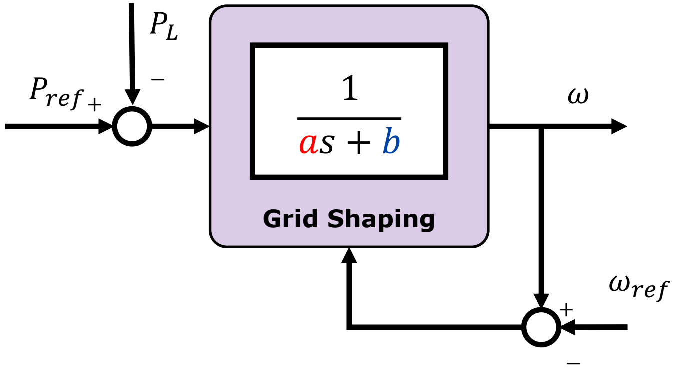
Tunable Performance:

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

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

Grid-shaping with GFL IBRs [TPS 21]





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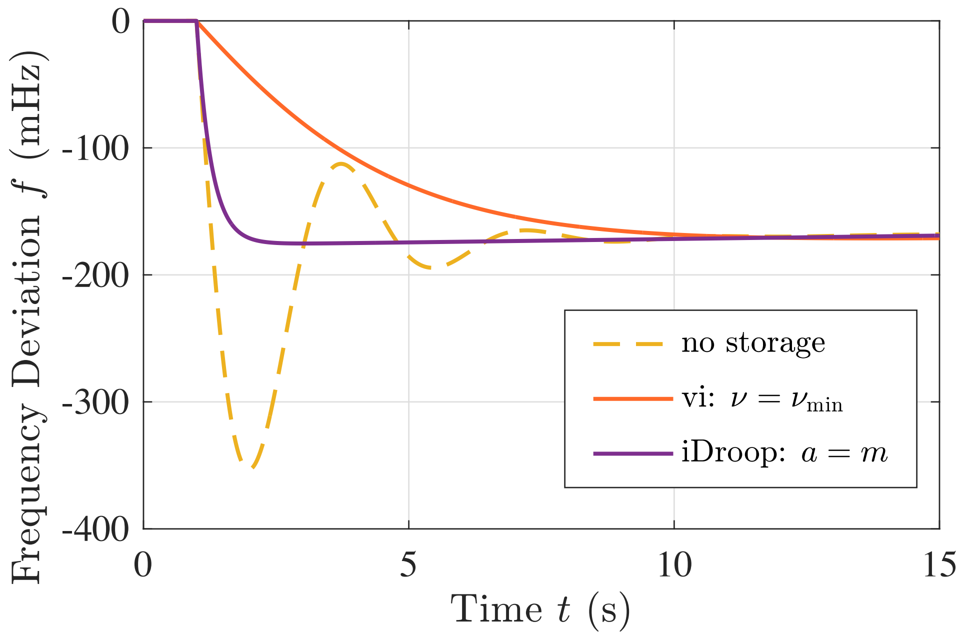
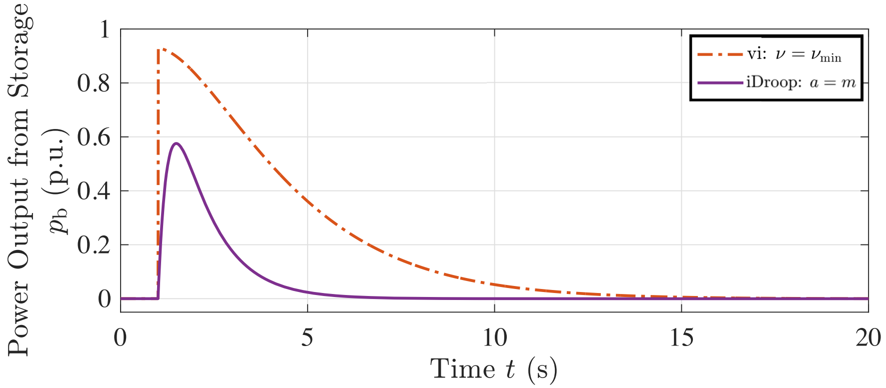
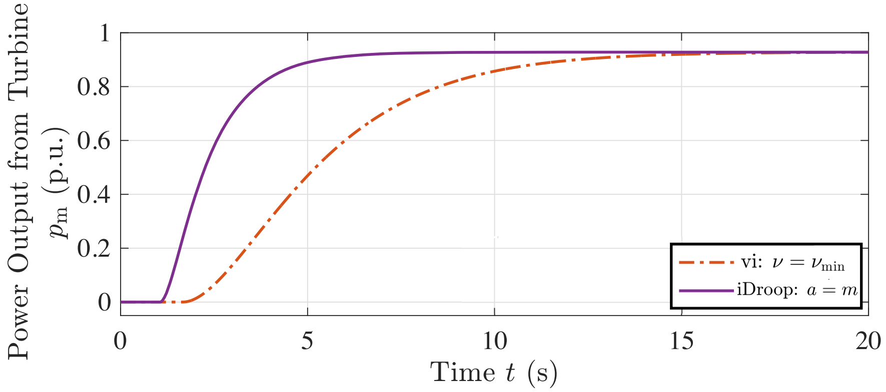
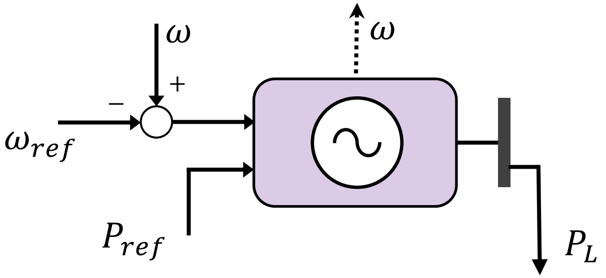


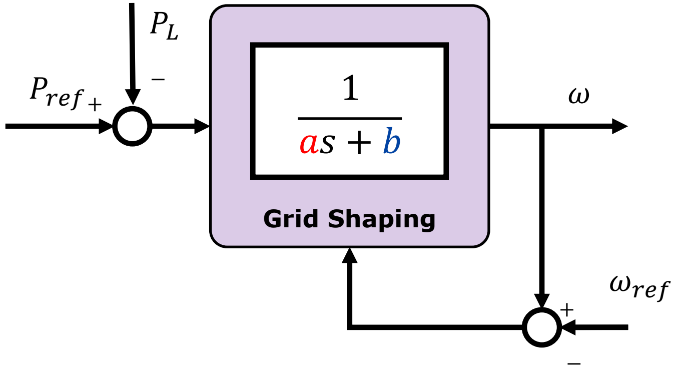




[TPS 21] Jiang, Cohn, Vorobev, M. Storage-based frequency shaping control **TPS 2021**

Grid-shaping with GFL IBRs [TPS 21]





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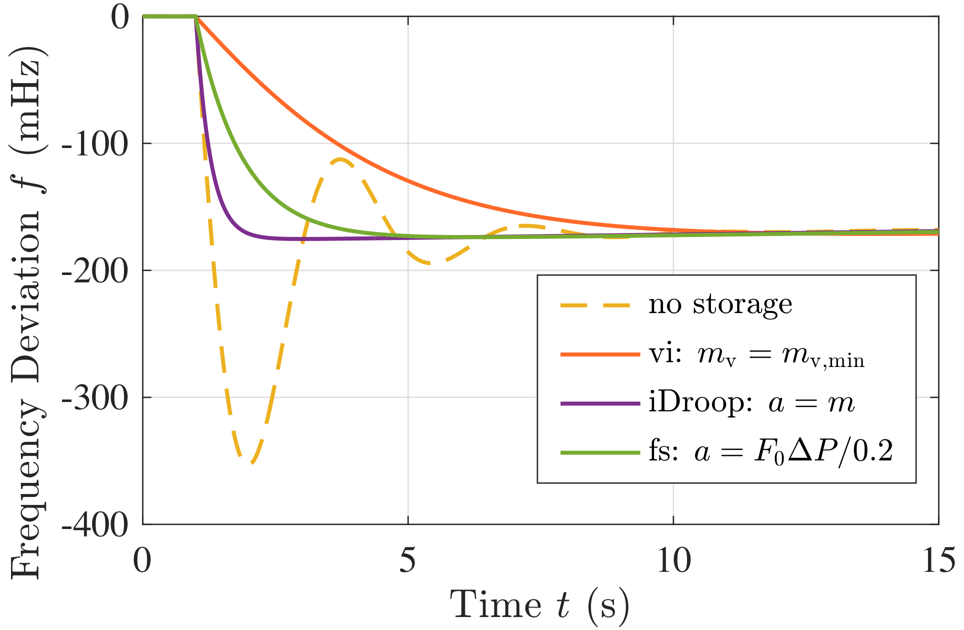


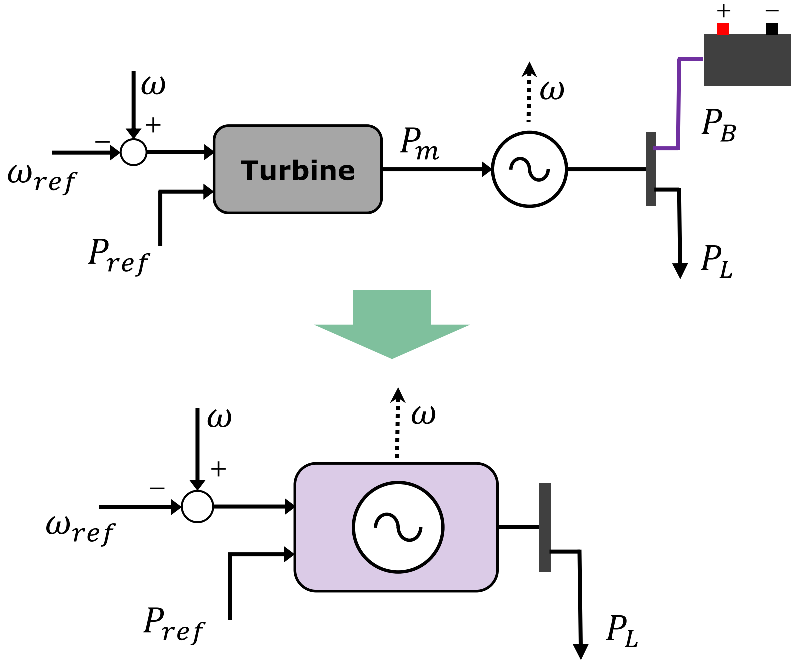
[TPS 21] Jiang, Cohn, Vorobev, M. Storage-based frequency shaping control **TPS 2021**

Grid Shaping Control

Use model matching control to shape SGs response

Grid-following IBRs

Grid-forming IBRs



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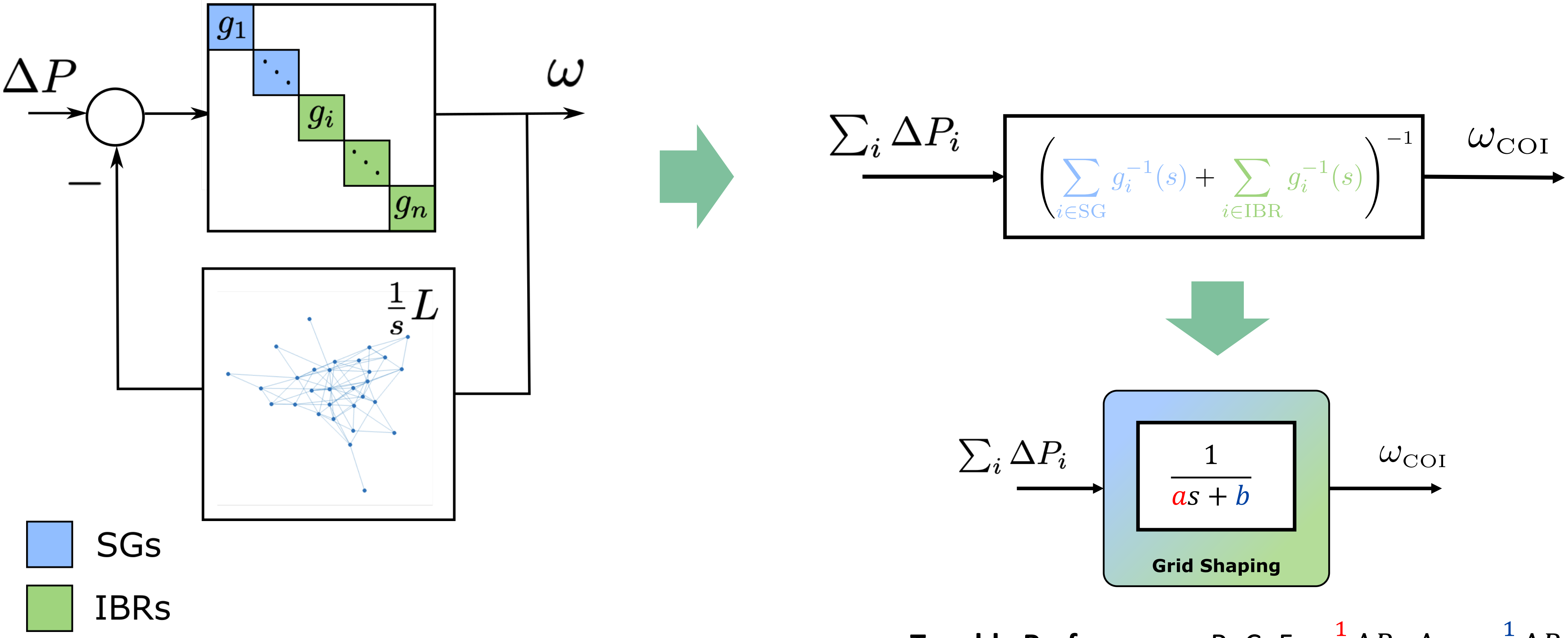
Grid-shaping with GFM IBRs [LCSS 20]



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

[LCSS 21] Jiang, Bernstein, Vorobev, M. Grid-forming frequency shaping control for low-inertia power systems **IEEE LCSS 2020**

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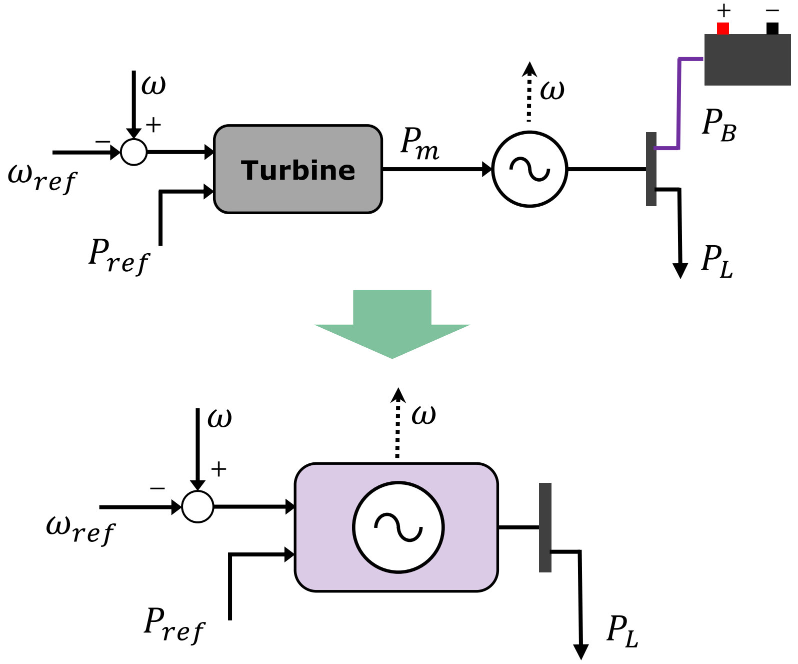
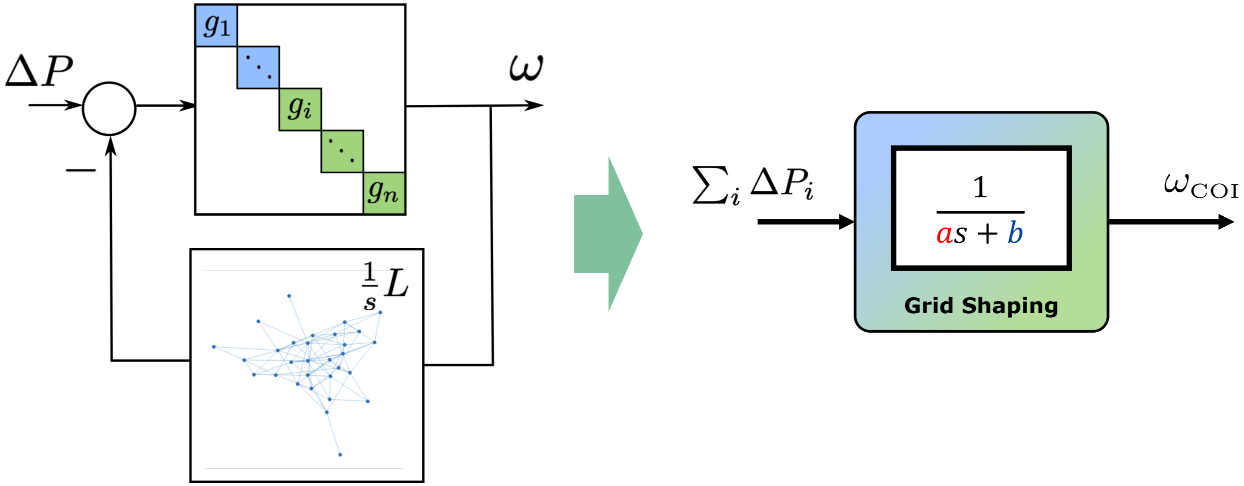
Use model matching control to shape SGs response

Grid-following IBRs



Grid-forming IBRs



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

Summary

- Merits and trade-offs of low inertia
    - Control Perspective: Lighter systems are easier to control!
- Analysis of IBR-rich Coherent Networks
    - Generalized Center of Inertia captures IBR dynamics
- Grid Shaping Control
    - Grid-following/forming control framework for future girds

Thanks!