Grid Shaping Control for High-IBR Power Systems

Stability Analysis and Control Design

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Johns Hopkins University

GE EDGE Symposium

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Acknowledgements

Students

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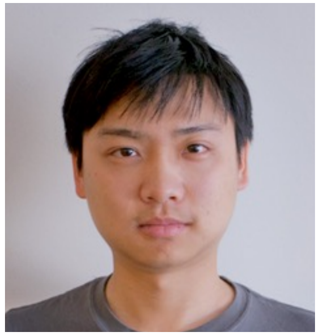

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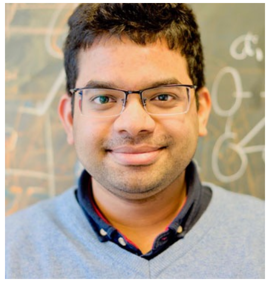

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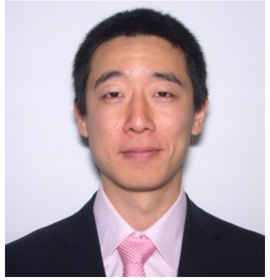

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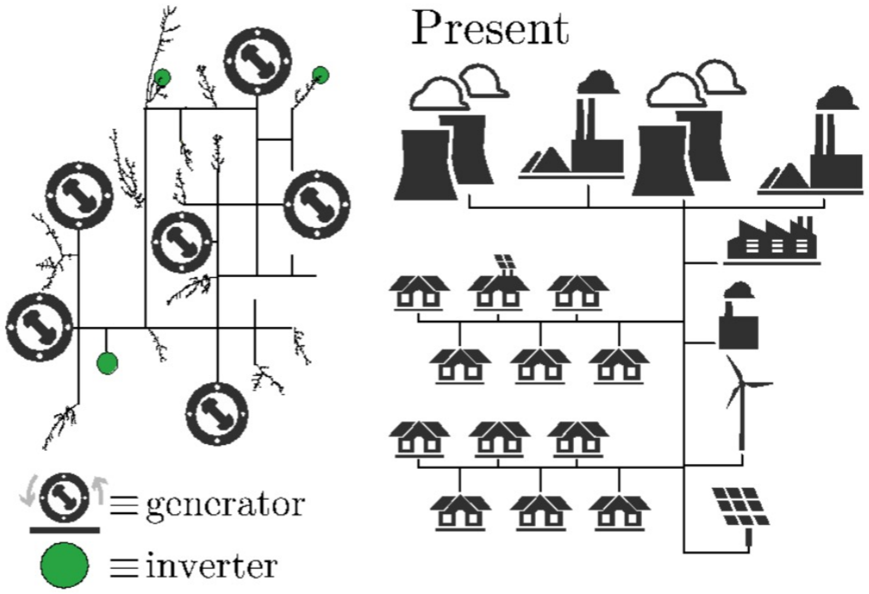
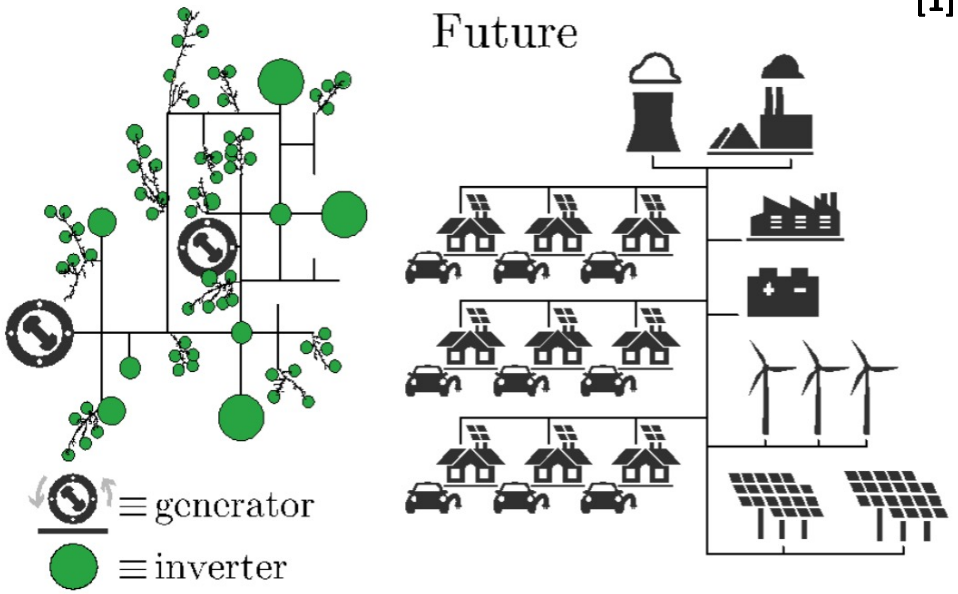
DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

The Future Grid

*[1]





Present grid

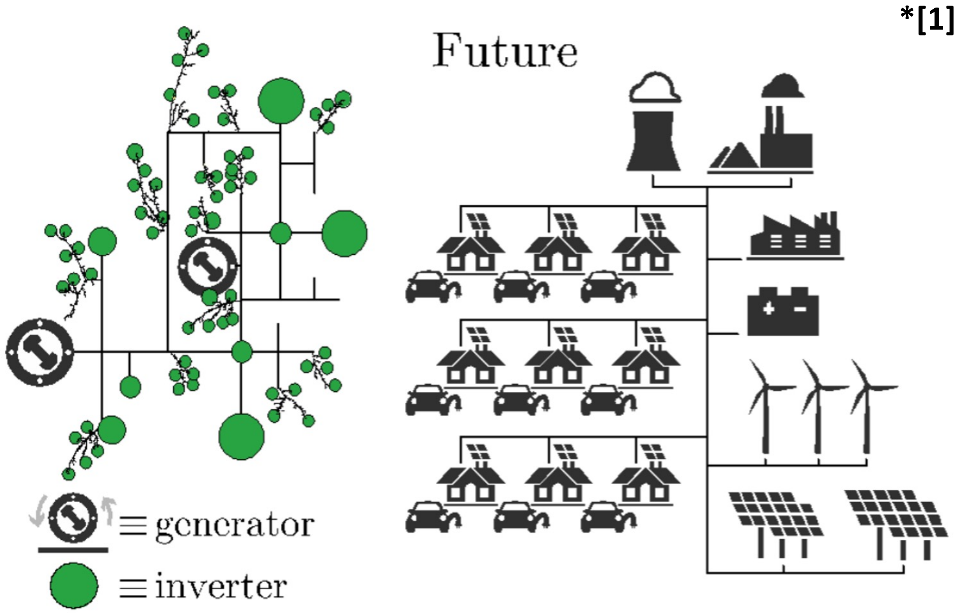
- dispatchable generation
- high inertial response
- strong voltage support
- well known physics

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



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!
- Scale-free Stability Analysis of Grids
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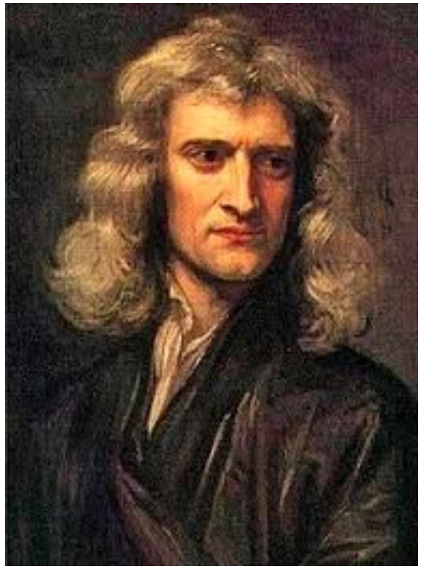
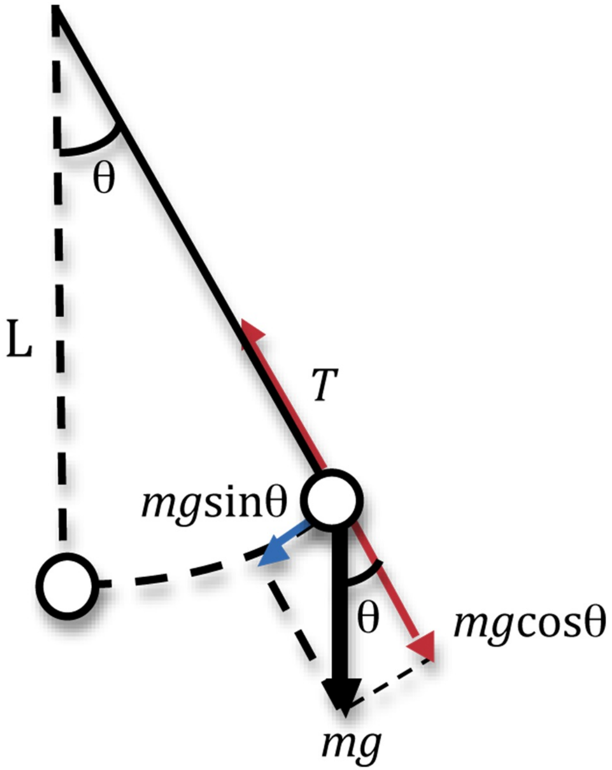
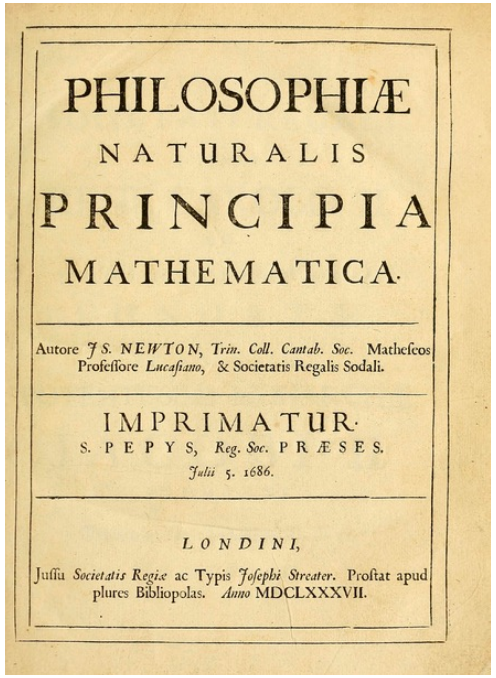
Merits and Tradeoffs of Inertia



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Julii 5. 1686.

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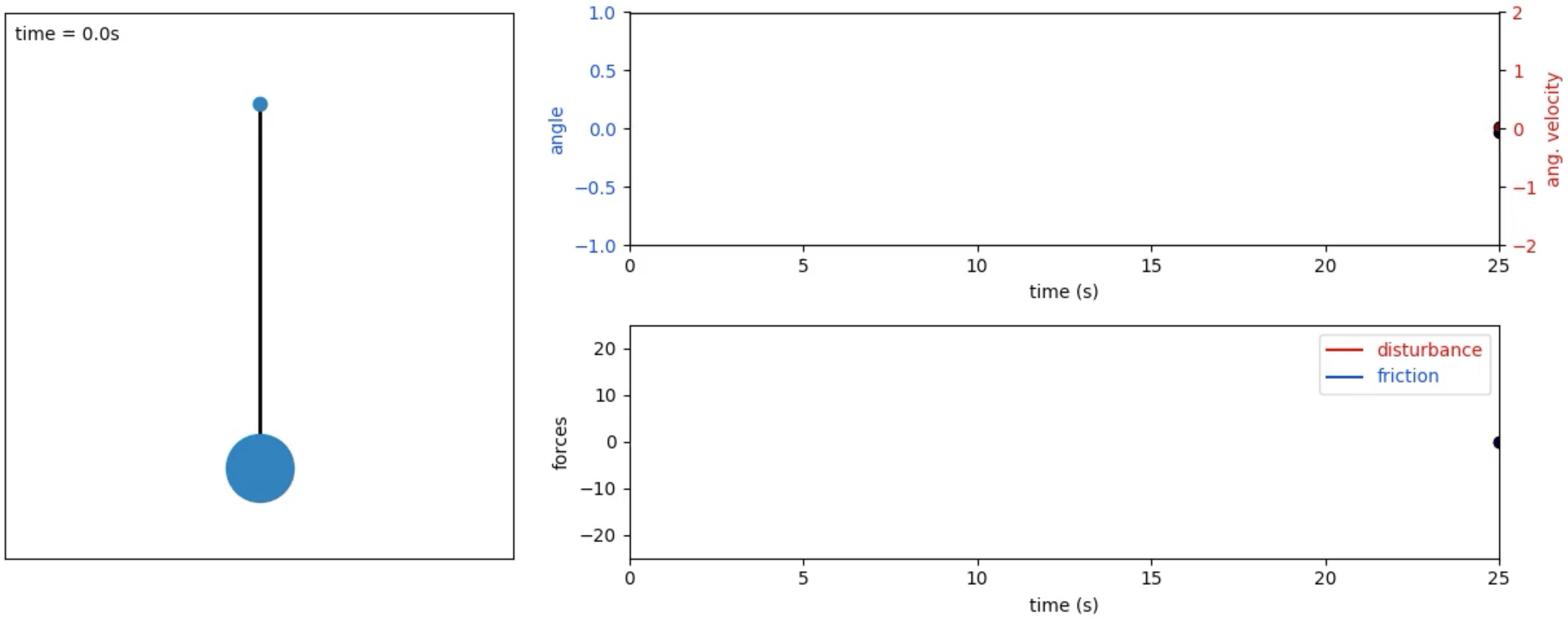
Juſſu Societatis Regiæ ac Typis Joſephi Streater. Proſtat apud plures Bibliopolas. Anno MDCLXXXVII.

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

Merits and Trade-offs of Inertia

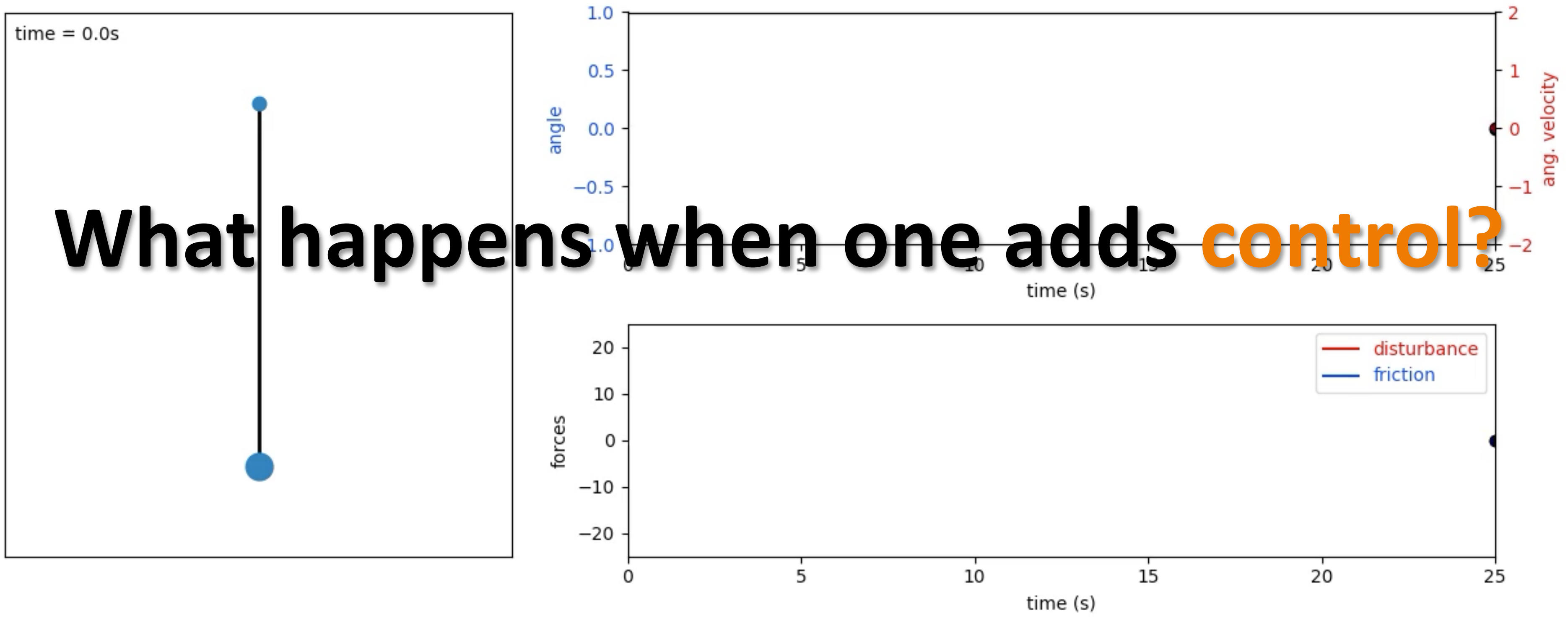
$$\ddot{\theta} = -\frac{d}{m}\dot{\theta} - g\sin\theta + \frac{f}{m}$$



Pros: Provides natural disturbance rejection **Cons:** Hard to regain steady-state

Merits and Trade-offs of Low Inertia

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



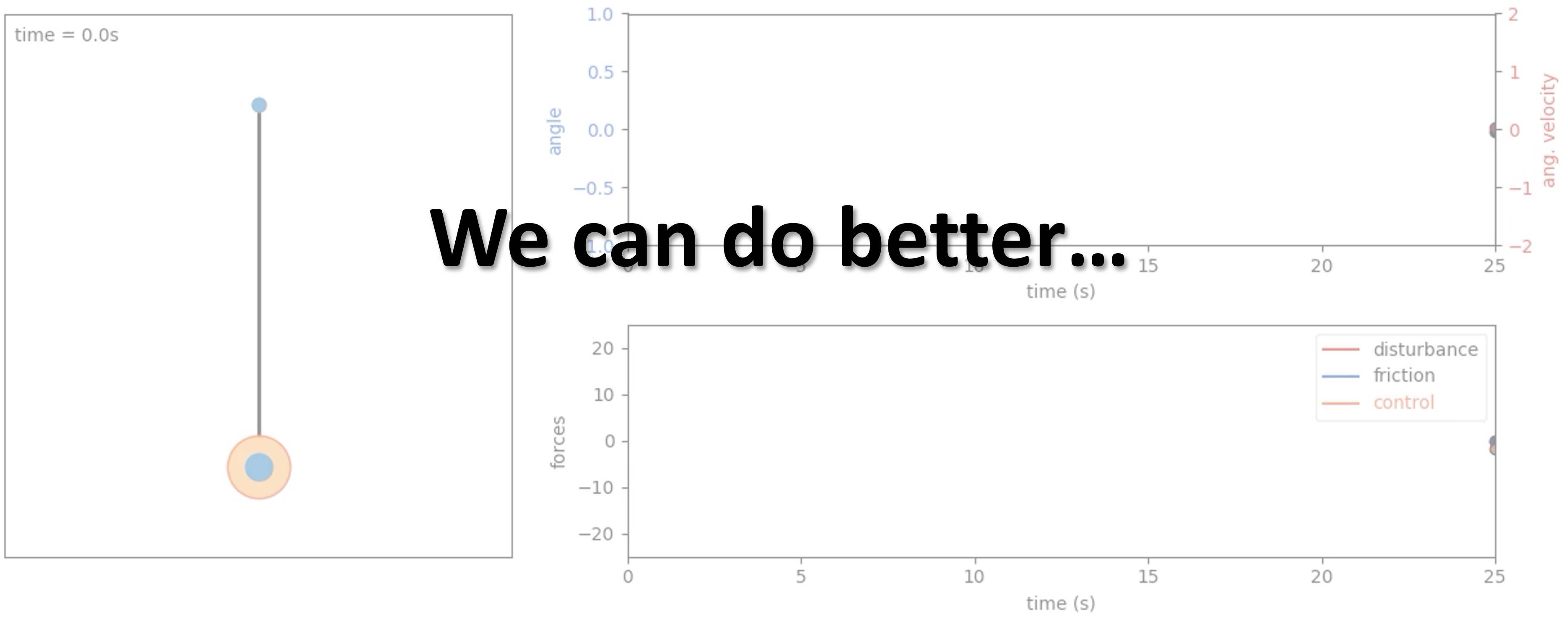
What happens when one adds control?

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**

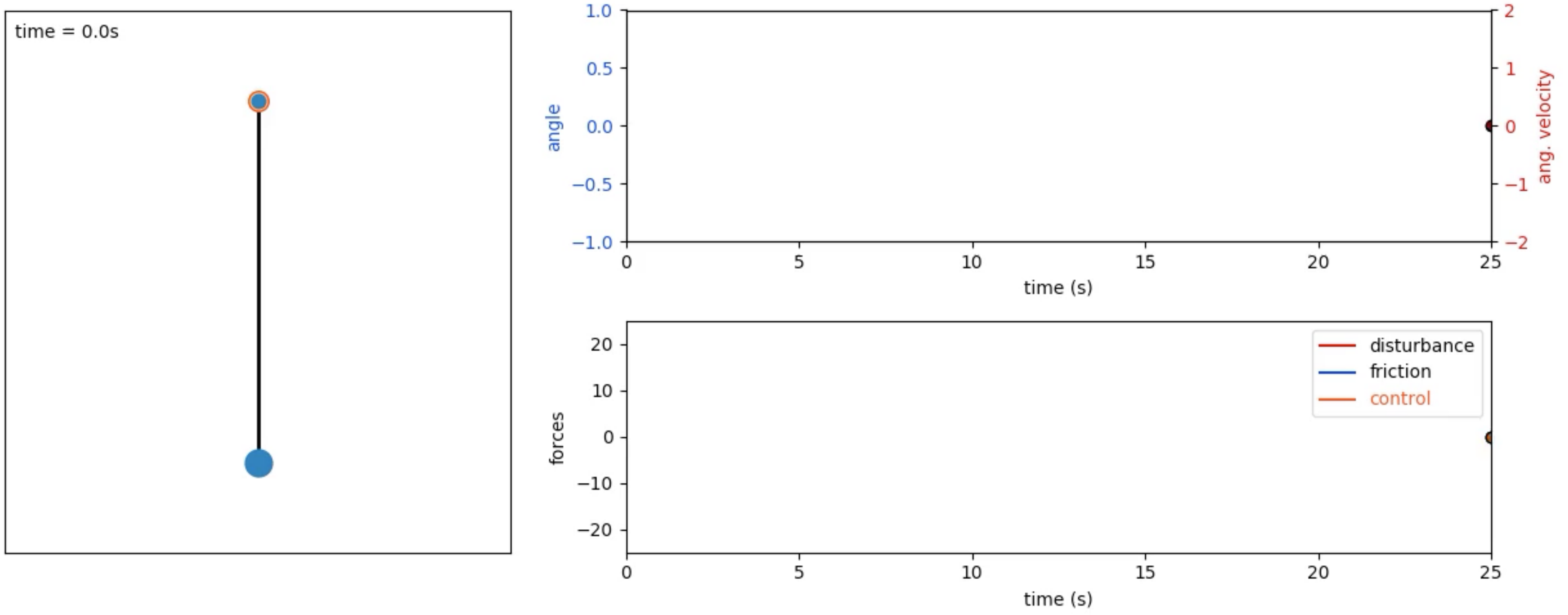
Control of Low Inertia Pendulum

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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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
- Disturbance Rejection
- Noise Attenuation
- 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**

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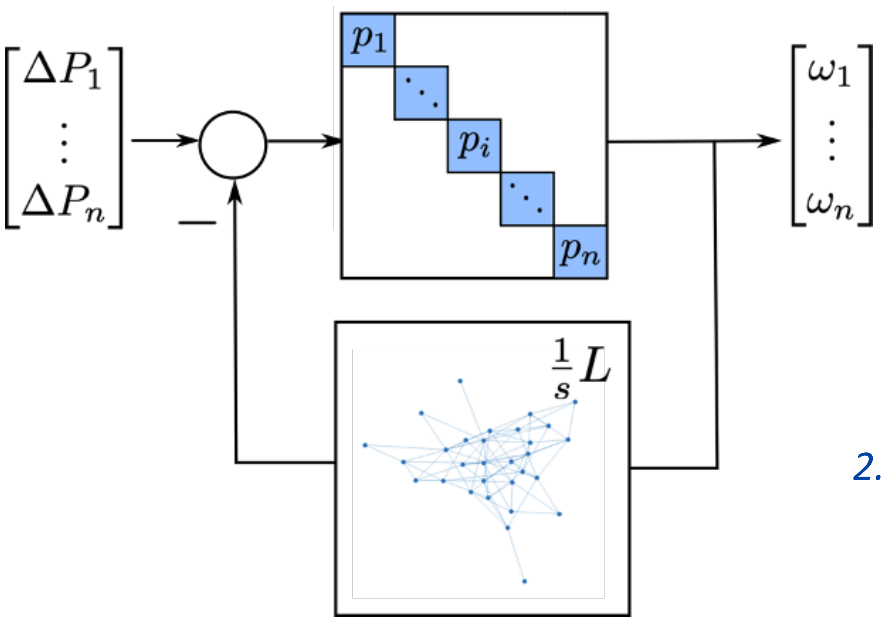
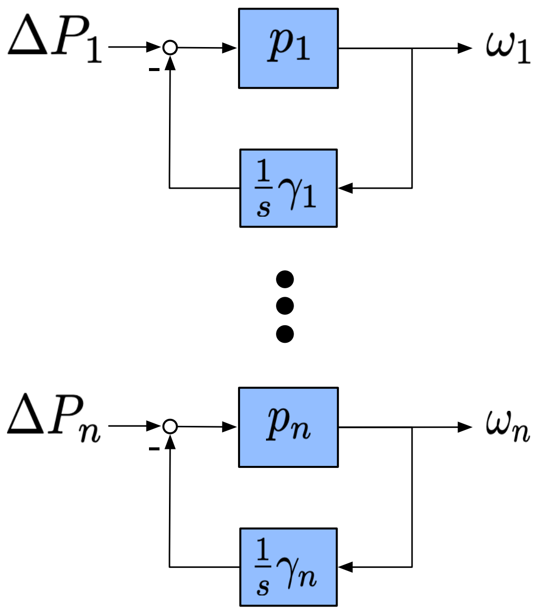
Decentralized Stability Analysis in Power Grids [TCNS 19]

Richard Pates



1.When does this interconnection is stable?

2. Can we do analysis and control design based on ***local rules****?*



Problem Setup:

- *Linearized* power flows, *lossless*

$$L_{ij} = b_{ij} v_i v_j \cos(\theta_i^* - \theta_j^*)$$

- Bus i: arbitrary *siso* transfer function:

$$\omega_i = p_i(s)\, \Delta P_i \quad \text{(SGs or IBRs)}$$

[TCNS 19] Pates, M. Robust Scale Free Synthesis for Frequency Regulation in Power Systems. **IEEE Transactions on Control of Network Systems, 2019**

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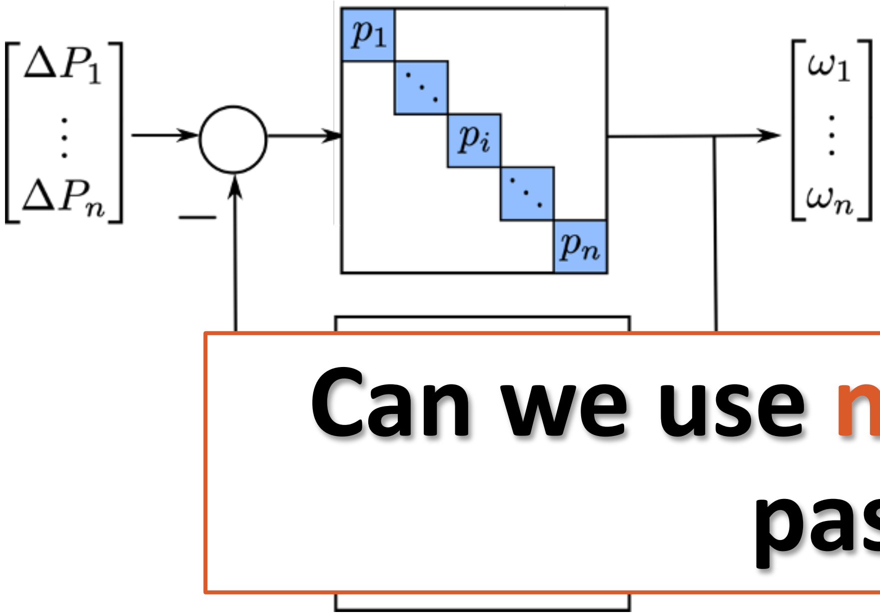

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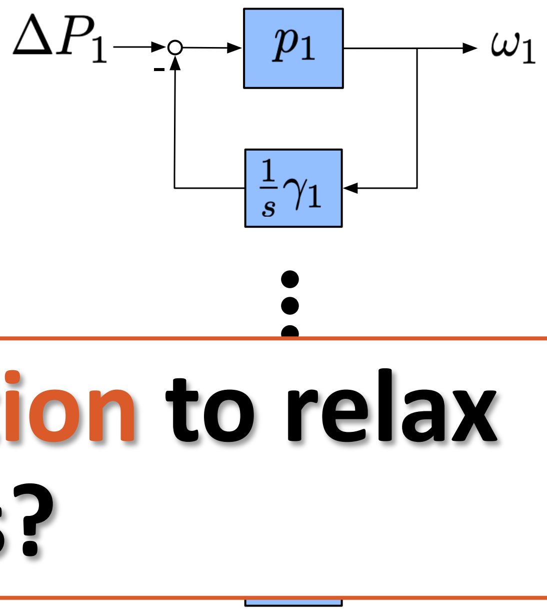


Richard Pates

Can we use network information to relax passivity conditions?

Standard Approach: Passivity

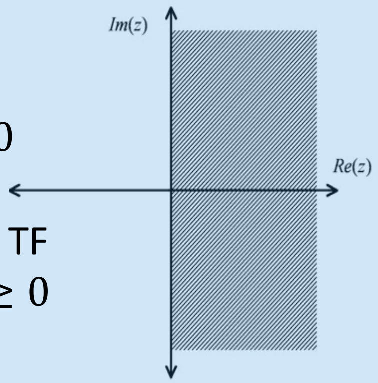
- If $p_i(s)$ is strictly positive real (SPR), then the interconnection is stable for **all networks L!**

Positive Real (PR) TF

$$\text{Re}[p_i(s)] \geq 0$$

Strictly Positive Real TF

$$\text{Re}[p_i(s-\varepsilon)] \geq 0$$



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Classical Result: Absolute Stability

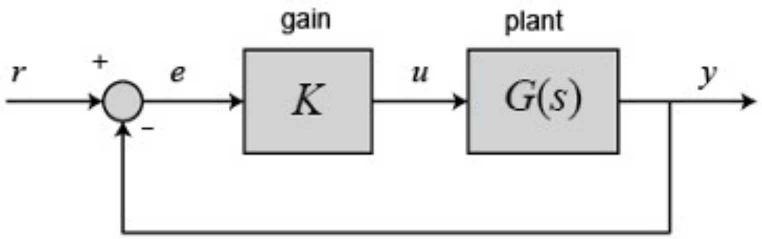
IEEE TRANSACTIONS ON AUTOMATIC CONTROL

Frequency Domain Stability Criteria—Part I

R. W. BROCKETT, MEMBER, IEEE AND J. L. WILLEMS

Abstract—The objective of this paper is to illustrate the limita-

II. THE GENERALIZED POPOV THEOREM

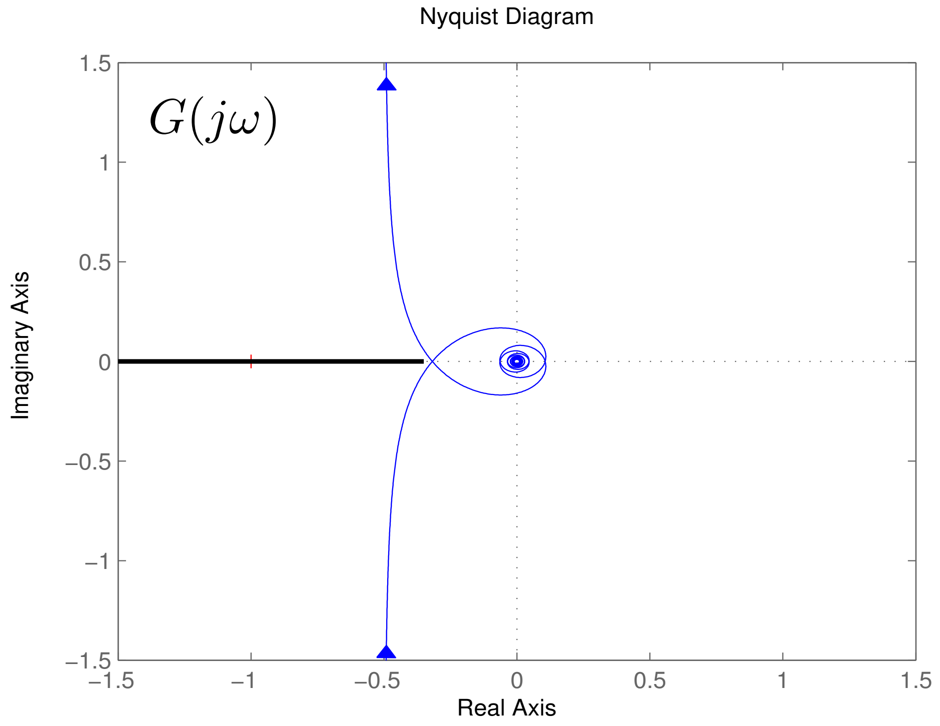


Stable for $0 \leq K \leq k^*$?

Assume: $G(s)$ is stable

Define: $h(s) \in PR$ (passive)

Test: If $h(s)\big(1 + k^* G(s)\big) \in SPR$ (strictly passive)
then, **yes!**



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Classical Result: **Absolute Stability**

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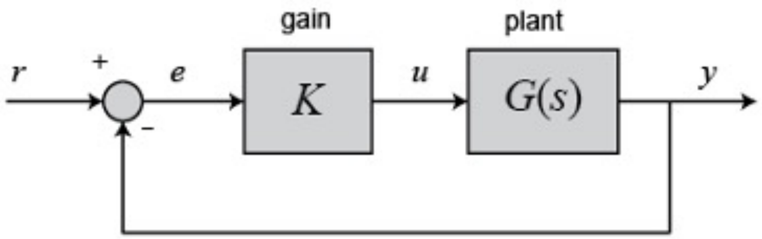

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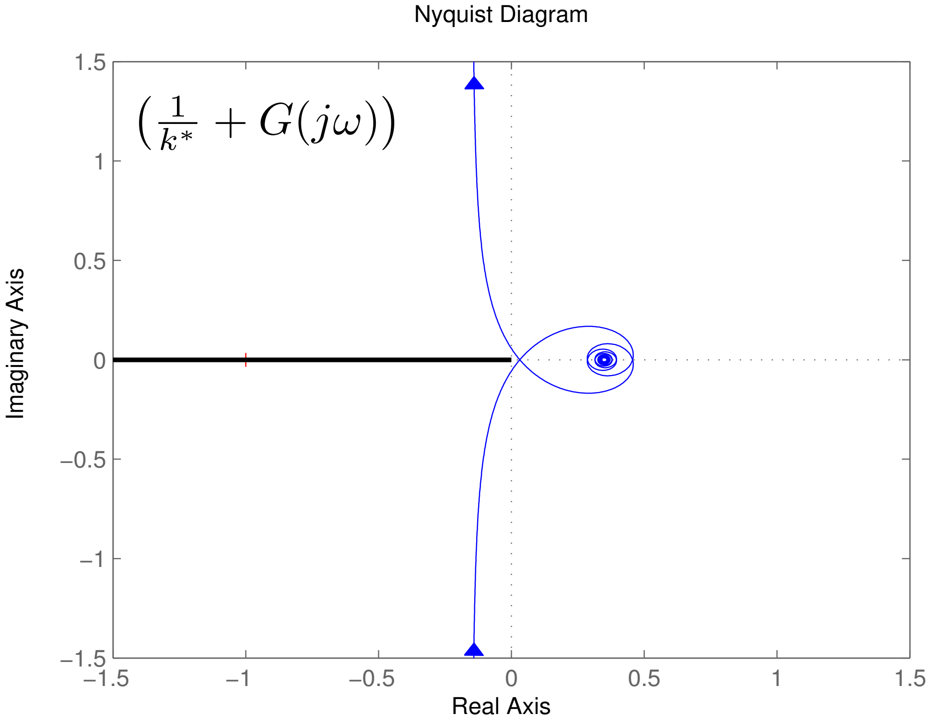

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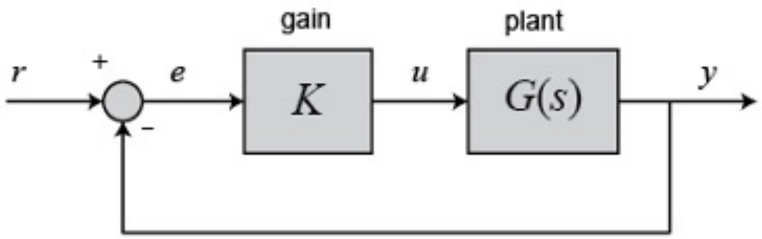

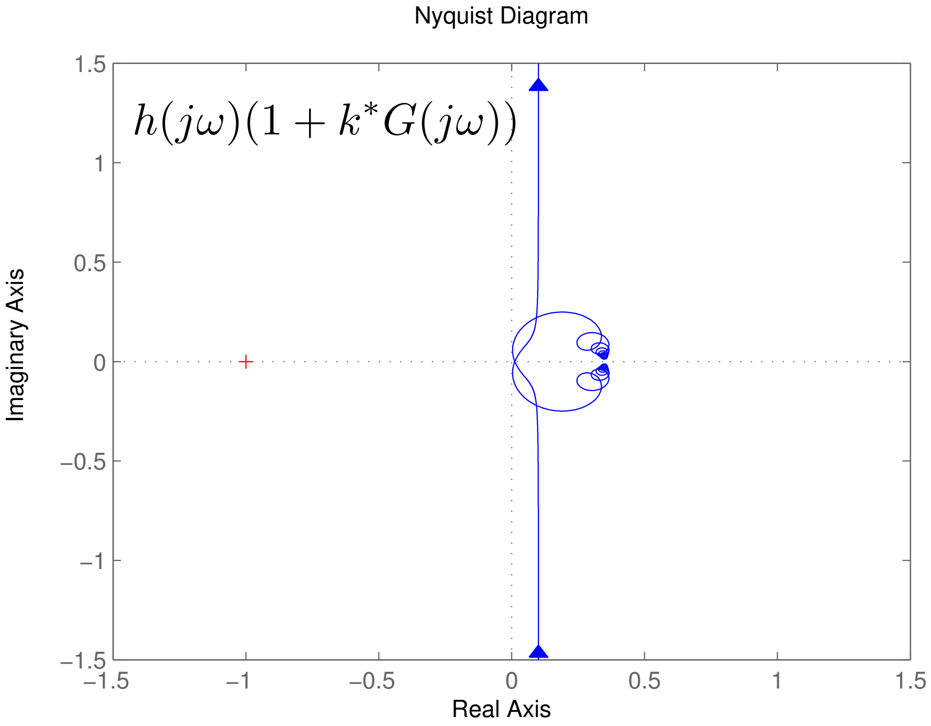

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Assume: $G(s)$ is stable

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[TCNS 19] Pates, M. Robust Scale Free Synthesis for Frequency Regulation in Power Systems. **IEEE Transactions on Control of Network Systems, 2019**

Scale-free Stability Analysis

Key Idea: Exploit limited network information to relax passivity condition

- Let γ_i be a local connectivity bound: $[L]_{ii} = \sum_{j \in N_i} L_{ij} \leq \frac{\gamma_i}{2}$

Brockett & Willems '65

Assume: $G(s)$ is stable

Define: $h(s) \in PR$ (passive)

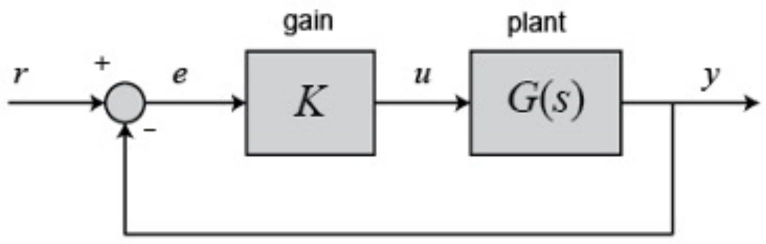
Test: If $\boldsymbol{h(s)\left(1 + k^* G(s)\right) \in SPR}$ (strictly) then system is stable for all $0 \leq K \leq k^*$

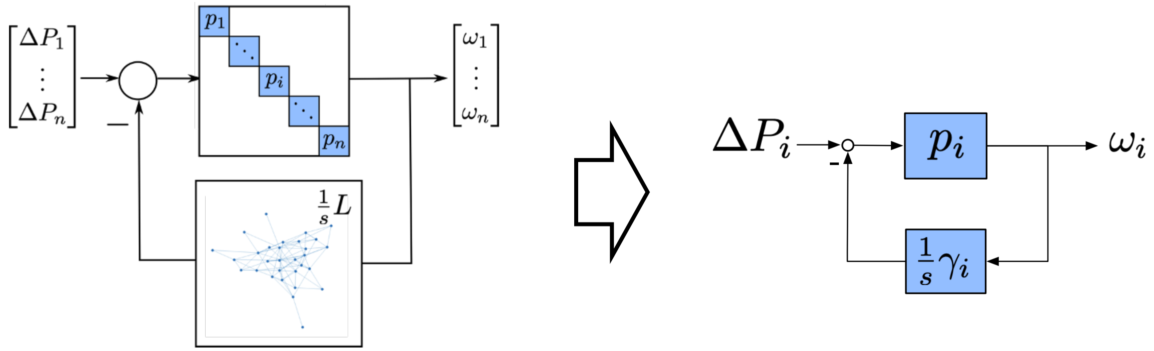
Pates & Mallada 2019

Assume: $p_i(s)$ is stable

Define: $h(s) \in PR$ (passive)

Test: If $\boldsymbol{h(s)\left(1 + \gamma_i \frac{1}{s} p_i(s)\right) \in SPR, \forall i}$, then system stable for networks $[L']_{ii} \leq \frac{\gamma_i}{2}, \forall i$





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Grid Shaping Control

Use model matching control to shape system response

Grid-following IBRs

Grid-forming IBRs

Grid-shaping with GFL IBRs [TPS 21]

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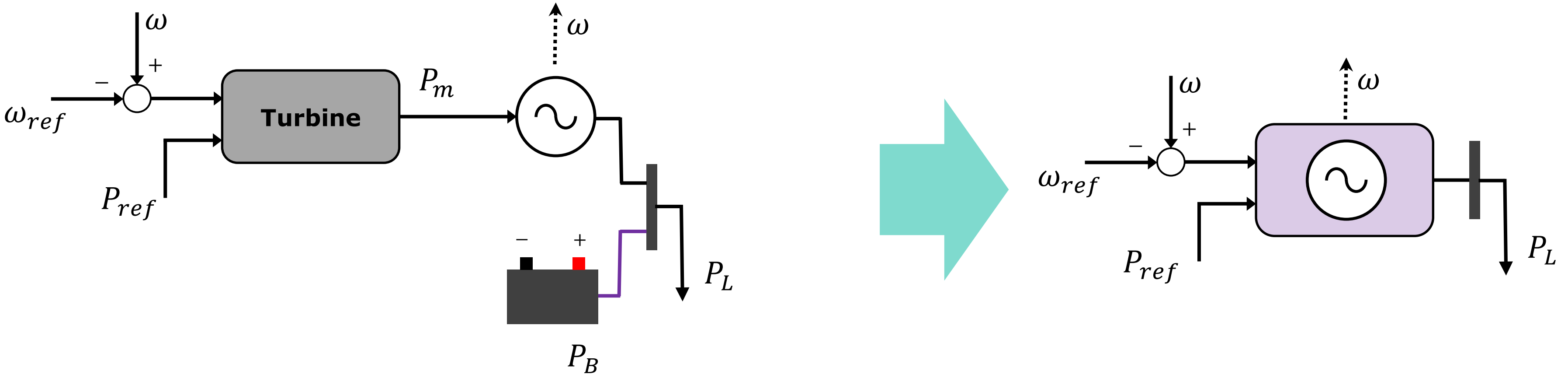

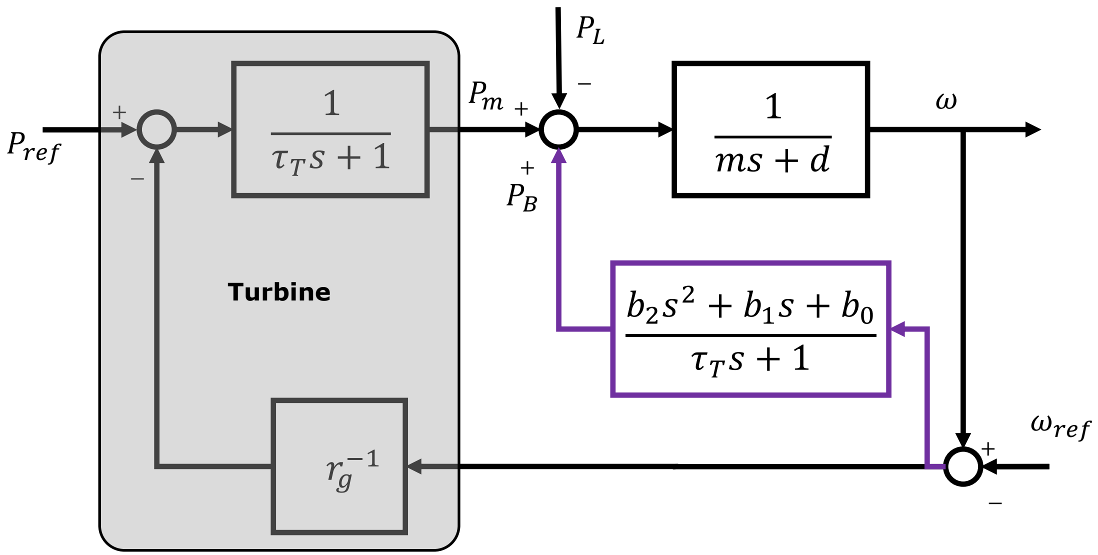

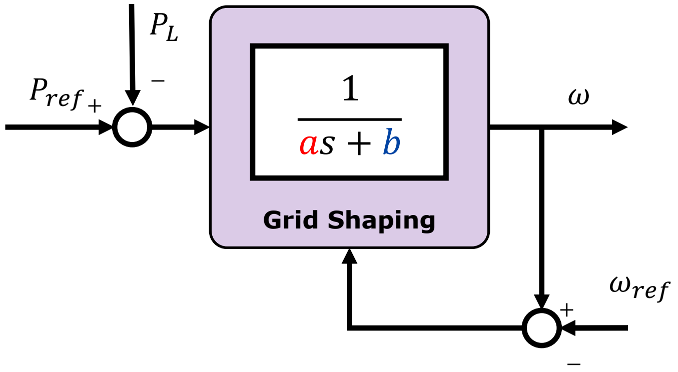

Tunable Performance:

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

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

Grid-shaping with GFL IBRs [TPS 21]


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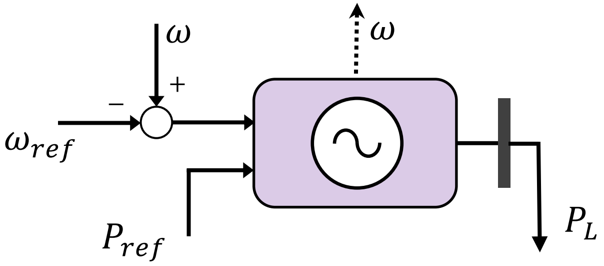

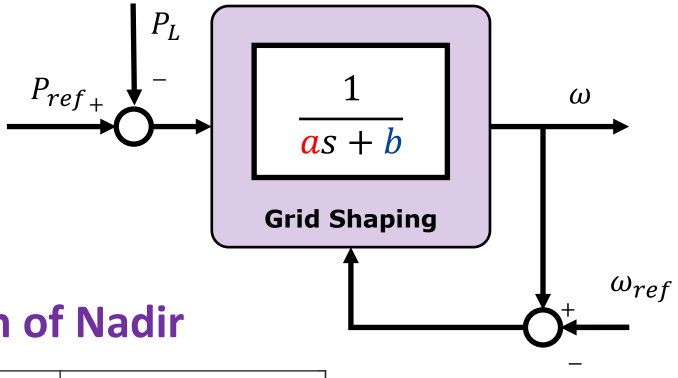

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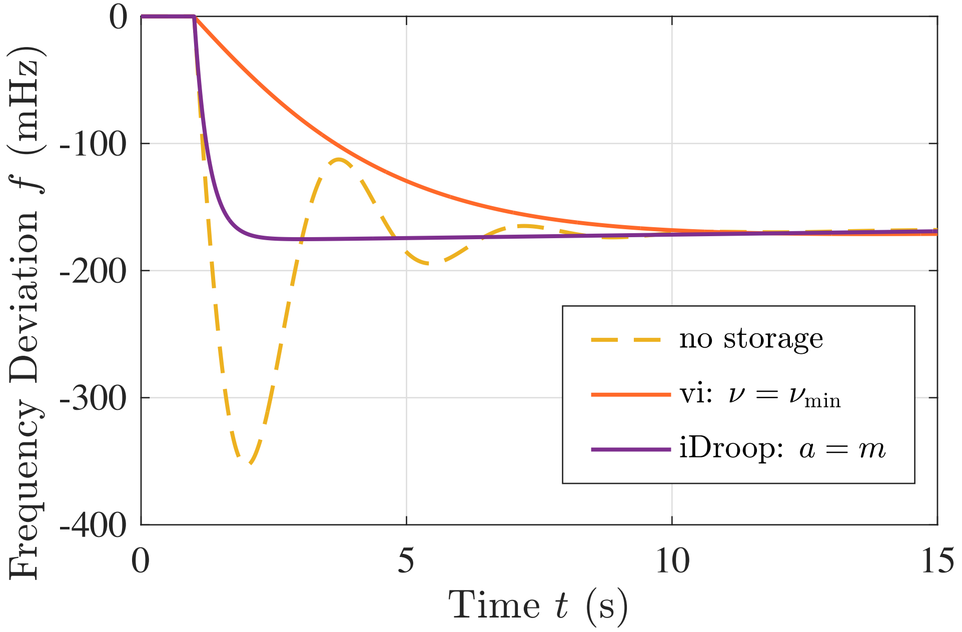
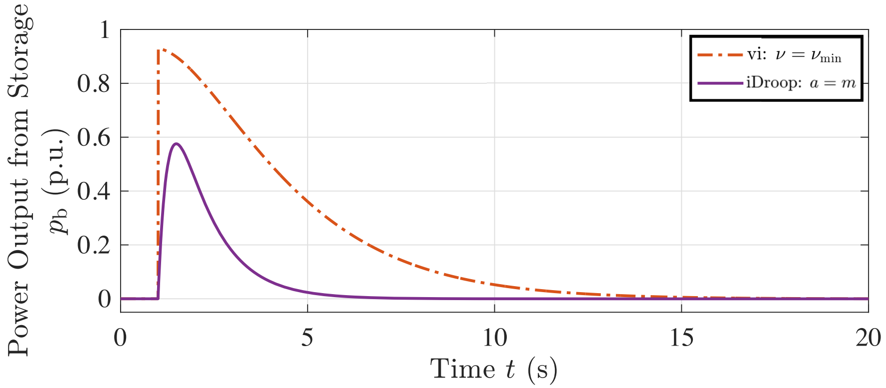
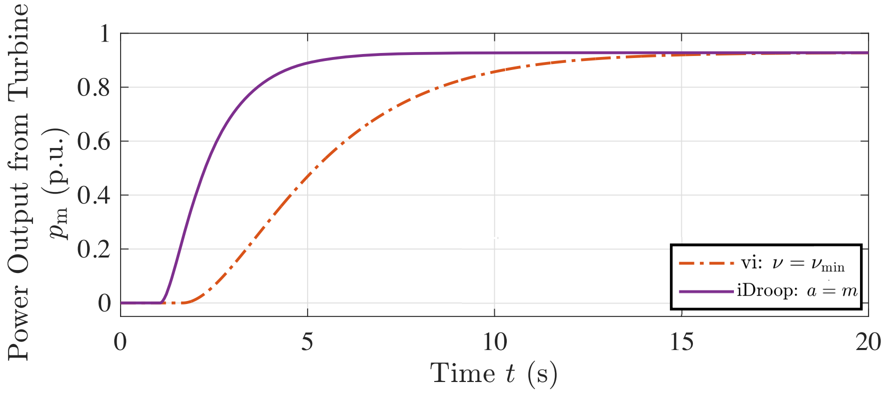
Example: Efficient Elimination of Nadir







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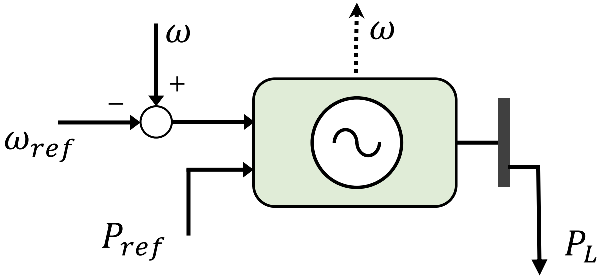
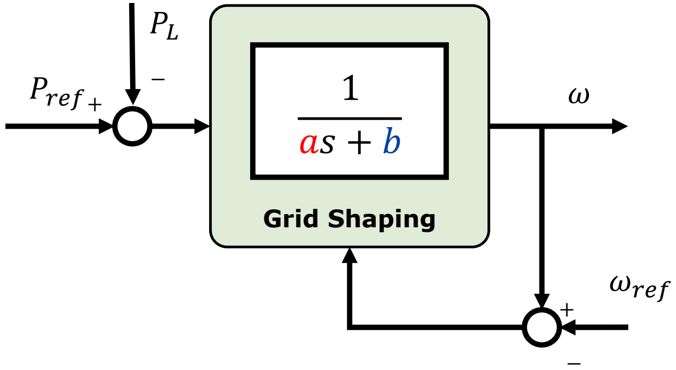
Grid-shaping with GFL IBRs [TPS 21]



Yan Jiang Eliza Cohn Petr Vorobev





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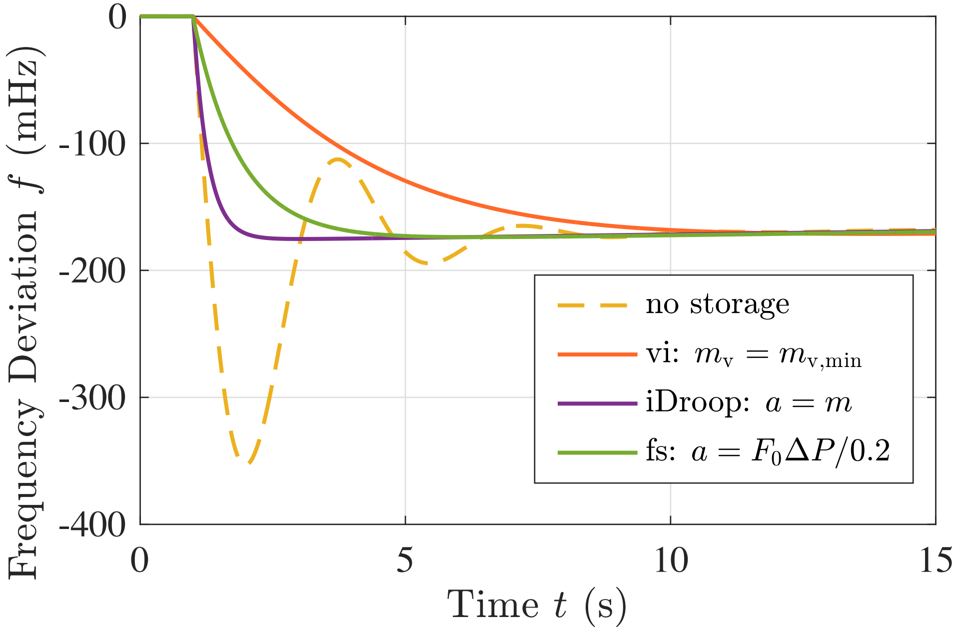
Example II: Tuning RoCoF



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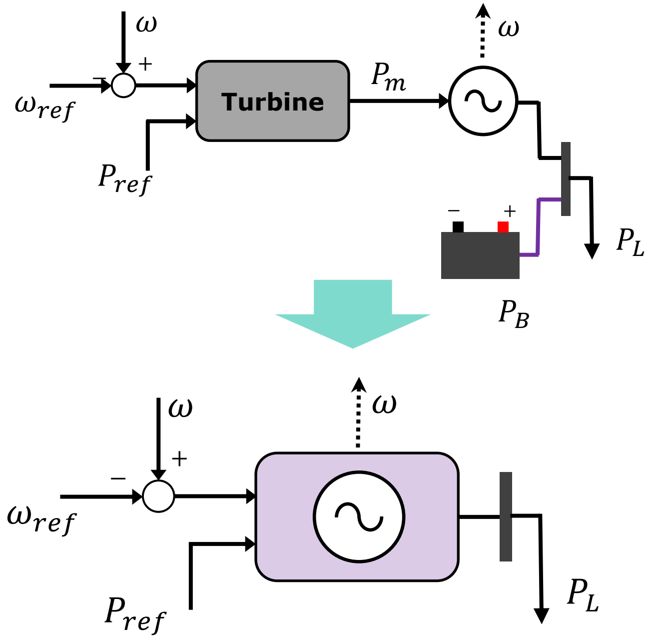
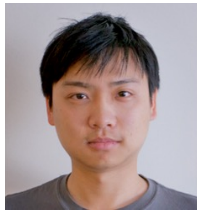


Tunable Performance:

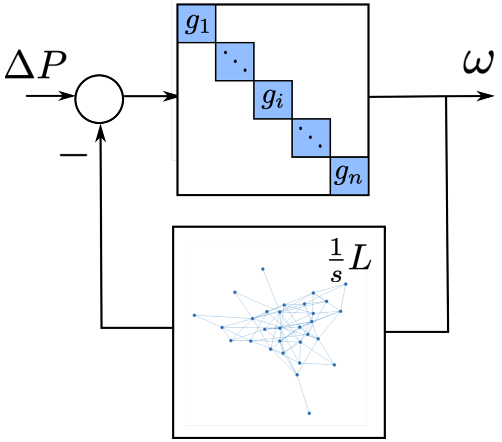
$$\text{RoCoF} = \frac{1}{a}\Delta P, \ \Delta\omega = \frac{1}{b}\Delta P$$

Grid-forming IBRs

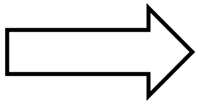
Generalized Center of Inertia (COI) [CDC 19,ArXiv 23]

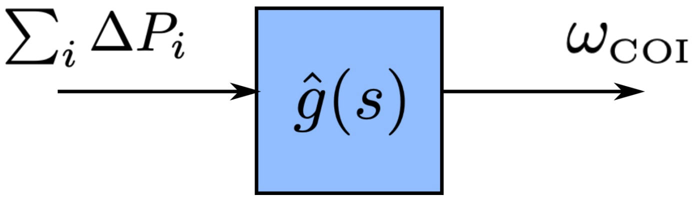


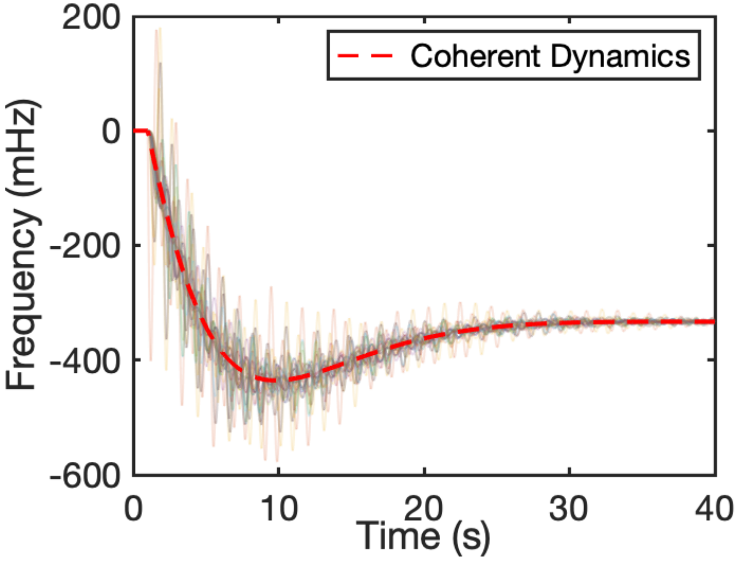

Hancheng Min Richard Pates



*What is the exact **response** of the **COI** of this network?*







Generalized COI:

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

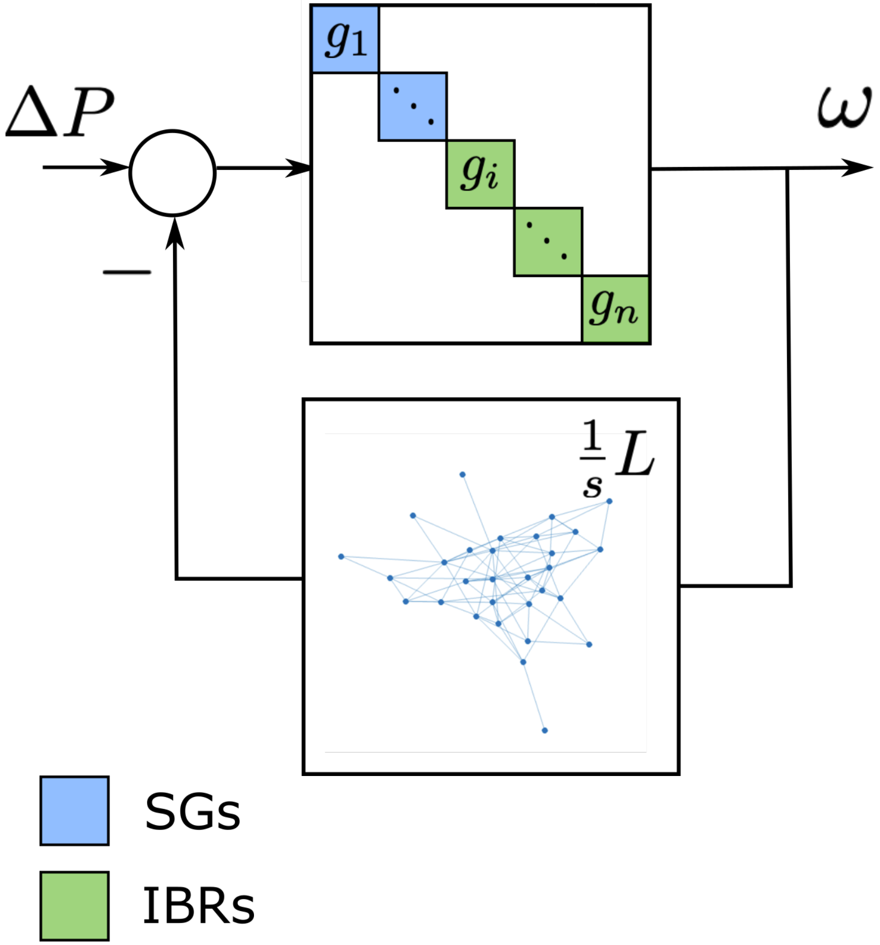
- **Properties of $\hat{g}(s)$:**
- Representation of aggregate response
- Accuracy of approximation:
  - is frequency dependent
  - increases with network connectivity
- Provides excellent template for reduced order models (via balance-truncations)

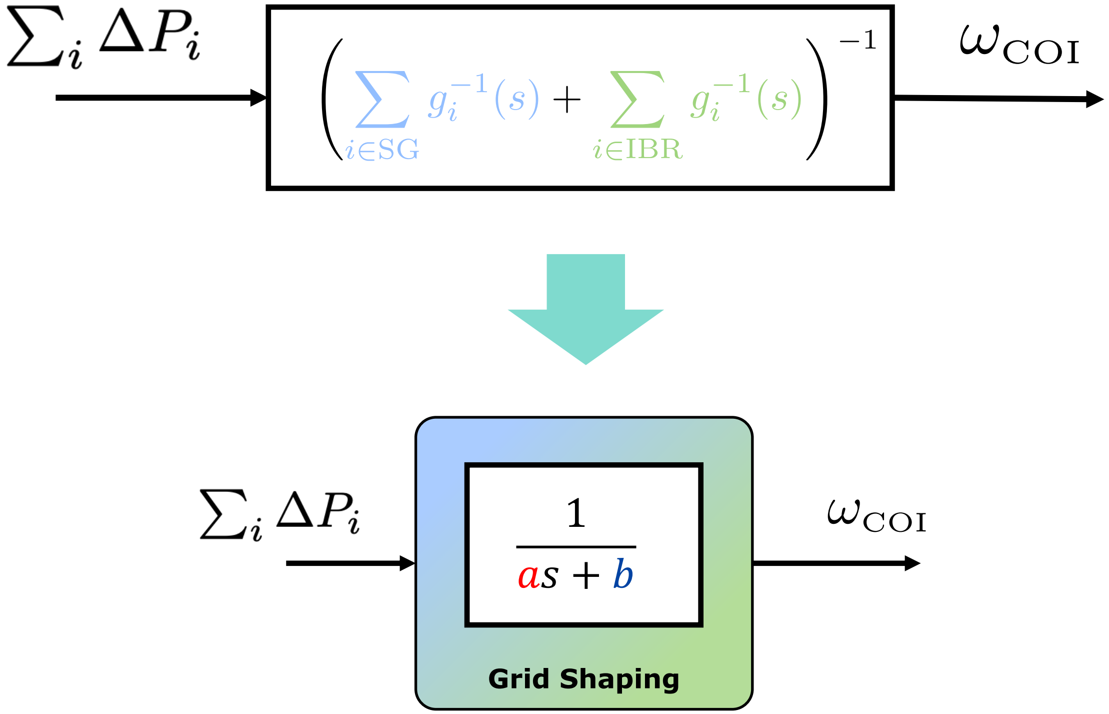
[CDC 19] Min, M. Dynamics concentration of large-scale tightly-connected networks. **Conference on Decision and Control 2019**

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

GFM System-wide Grid-shaping [LCSS 20]



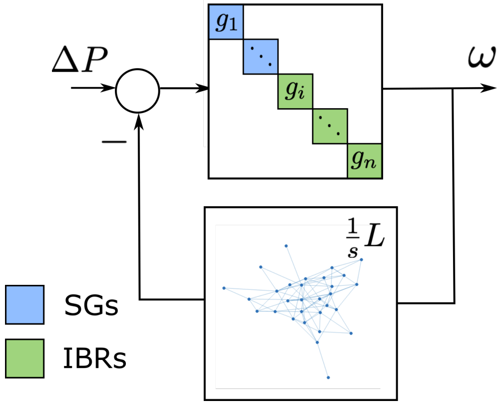


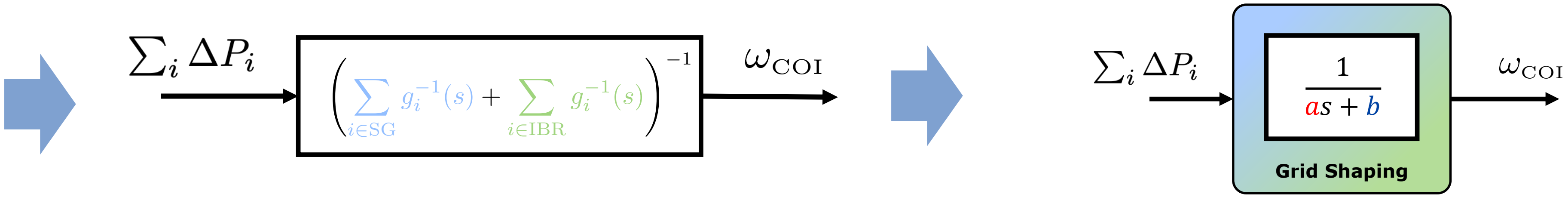


Tunable Performance: $\text{RoCoF} = \frac{1}{a}\Delta P, \ \Delta\omega = \frac{1}{b}\Delta P$

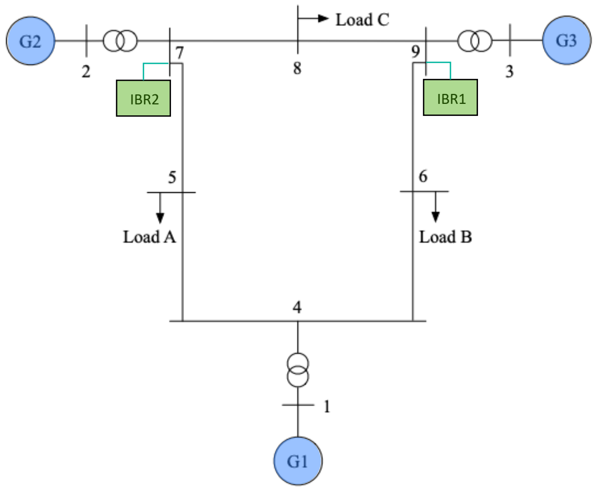
[LCSS 20] Jiang, Bernstein, Vorobev, M. Grid-forming frequency shaping control for low-inertia power systems **IEEE Control Systems Letters 2020**

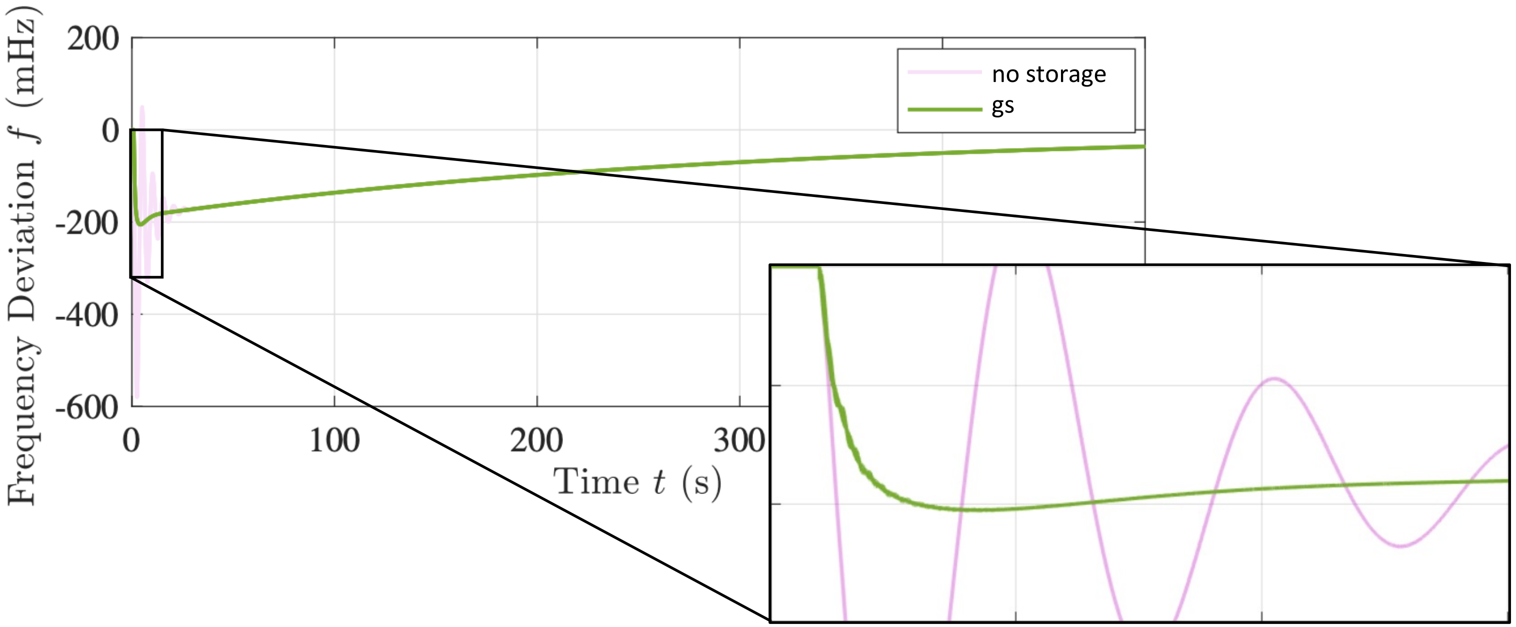
GFM System-wide Grid-shaping [LCSS 20]





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





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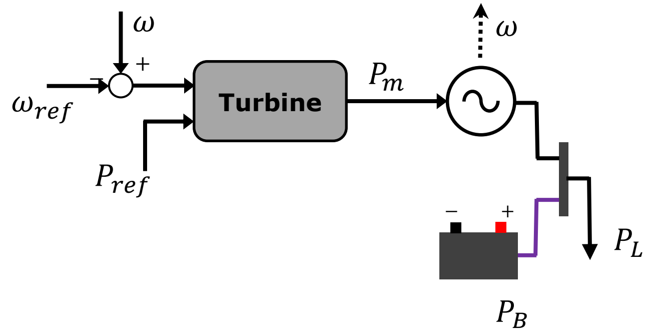
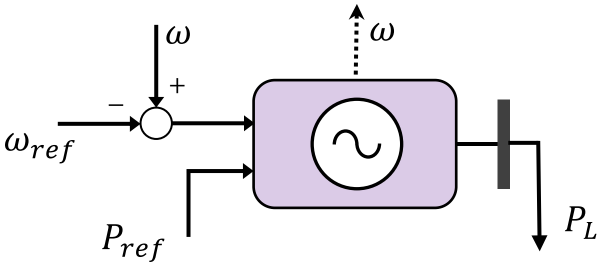
Grid Shaping Control

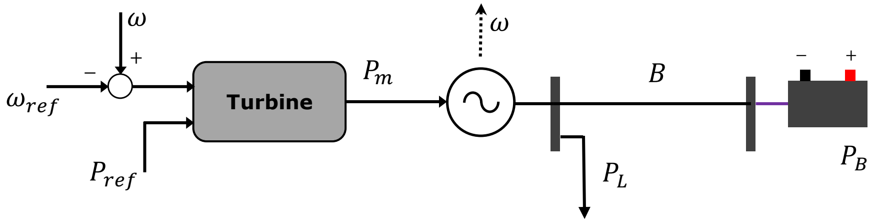
Use model matching control to shape system response

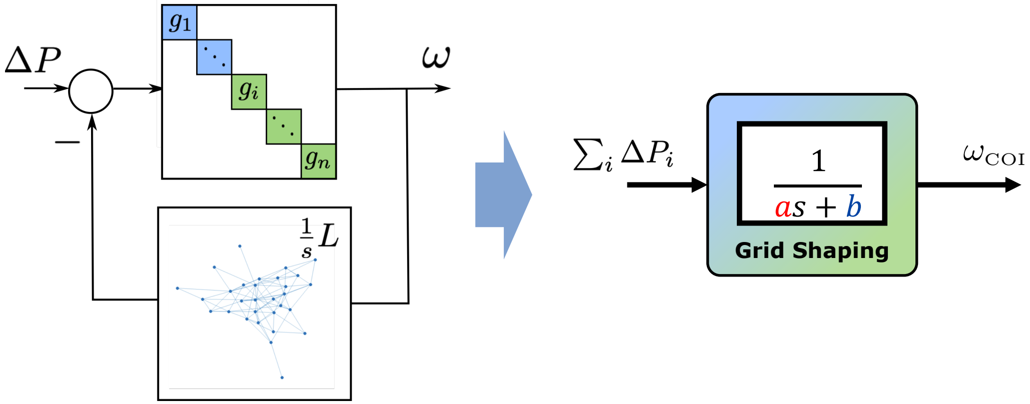
Grid-following IBRs





Grid-forming IBRs





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

Summary

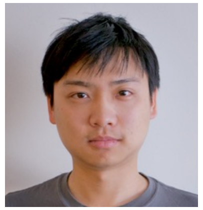
- **Merits and trade-offs of low inertia**
  - Control Perspective: Lighter systems are easier to control!
  - Smarter controller can provide multiple benefits in Nadir, RoCoF, inter-area oscillations, and disturbance rejection, with less effort

- **Scale-free Stability Analysis of Grids**
  - Generalizes passivity notions using network information
  - Decentralized test based on local models
  - Compatible with H_∞-synthesis methods

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

Thanks!


Yan Jiang


Hancheng Min

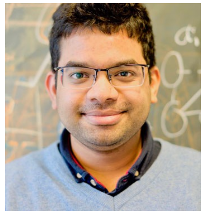

Eliza Cohn

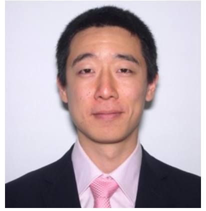

Petr Vorobev


Richard Pates


Fernando Paganini


Dominic Groß


Bala K. Poolla


Yashen Lin


Andrey Bernstein

Merits and trade-offs of low inertia

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Grid Shaping Control

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

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