

Secondary Frequency Control

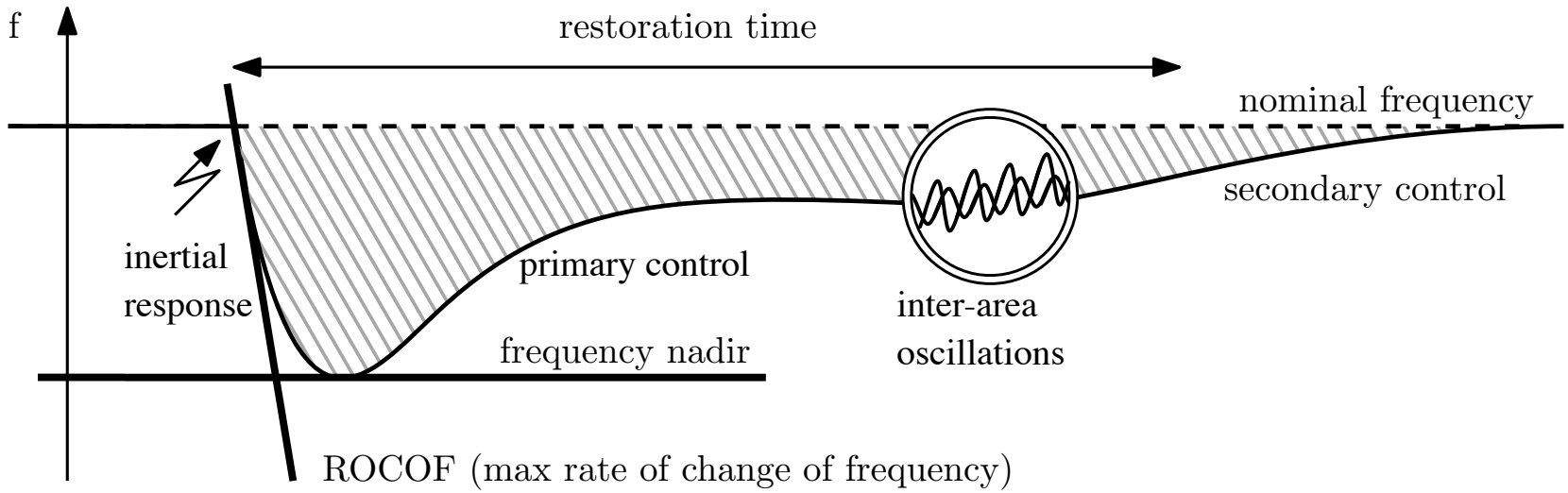
Florian Dörfler, ETH Zurich

EECI School M07, May 6-10, 2024, Barcelona

Outline

Outline

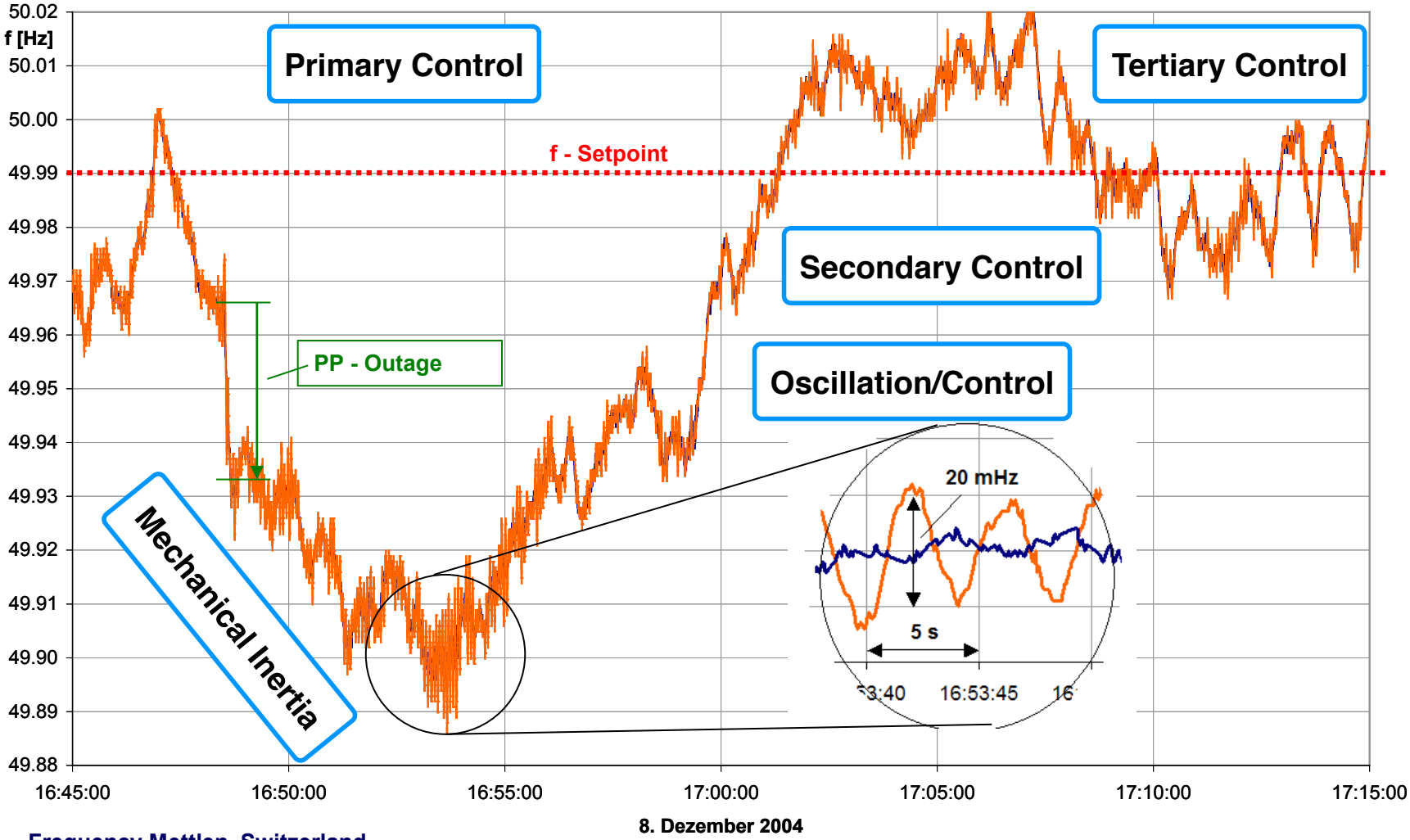
Disturbance response of **ideal** system



1. **physical inertia** instantly provides decentralized **derivative** control $\rightarrow M\dot{\omega}$
2. **decentralized primary** loops at devices provide **proportional** control $\rightarrow D\omega$
3. **system-wide secondary** loop provides centralized **integral** control $\rightarrow K\int \omega\, dt$

$\equiv$ disturbance rejection / regulation / **integral control**

Disturbance response of **real** system



Source: W. Sattinger, Swissgrid

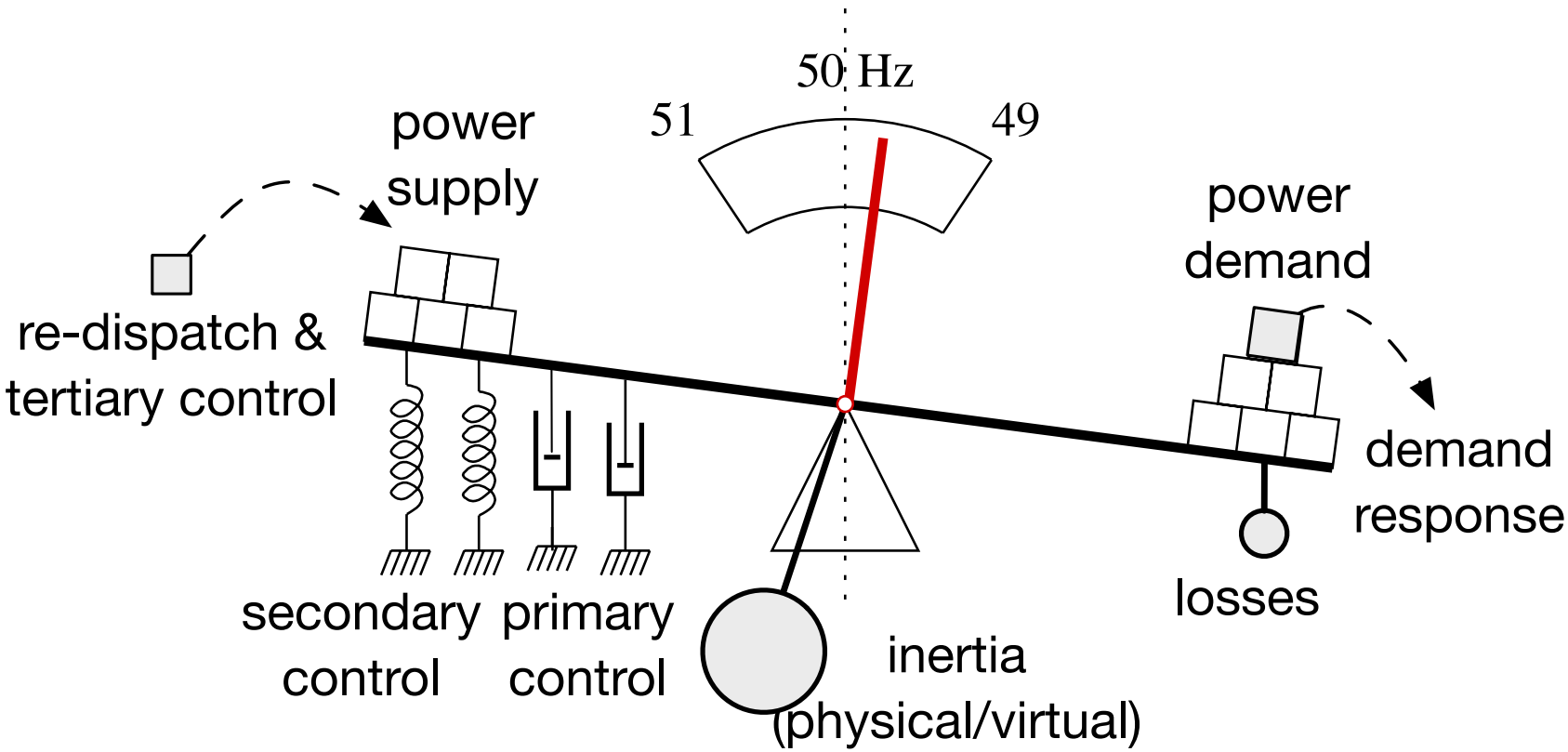
this lecture will focus on the tail of the curve: secondary control

Steady-state power system balancing

(covered on the board)

A refined mechanical analogue

(figure adapted from “Power system dynamics visualization . . . ” by F. Milano ’18)



When secondary control goes wrong . . .



Grid projects About us Customers de fr it en

swissgrid

6 March 2018 | News

Frequency deviation in continental European grid leads to grid time deviations

"The missing energy amounts currently to 113 GWh . . . The decrease . . . is affecting also those electric clocks that are steered by the frequency of the power system . . . they show currently a delay of close to six minutes."

– ENTSO-E press release

Outline

Secondary **integral** control fundamentals

(covered on the board)

#1 control objective: power balance

stylized, linearized, lossless, & low-order
swing dynamics + governor control
(all can be extended to detailed models)

$$\dot{\theta}_i = \omega_i$$
$$M_i \dot{\omega}_i = -D_i \omega_i + p_{i,\text{ref}} + u_i - p_i(\theta)$$

- $p_{i,\text{ref}}$ = net load / generation at bus i
- u_i = controlled governor power injection
- DC power flow $p_i(\theta) = \sum_j B_{ij}(\theta_i - \theta_j)$

synchronous steady state

$$\omega_i = \omega_{\text{sync}} \propto \sum_i (p_{i,\text{ref}} + u_i) \quad \forall i$$

$\rightarrow$ sync frequency $\propto$ power imbalance

control objective (simplified for now)

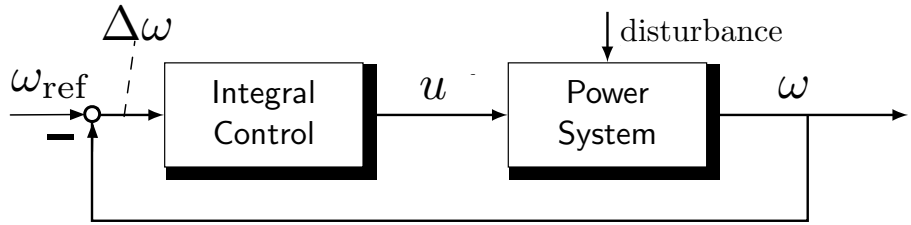
- power balance: $\sum_i p_{i,\text{ref}} + u_i = 0$

$\Leftrightarrow$ frequency regulation: $\omega_{\text{sync}} = 0$

- . . . to be achieved asymptotically (approximately during transients)
- . . . & with robust & simple control (decentralized or distributed)

main insight: balance objective $\propto \omega_{\text{sync}}$ can be measured locally !

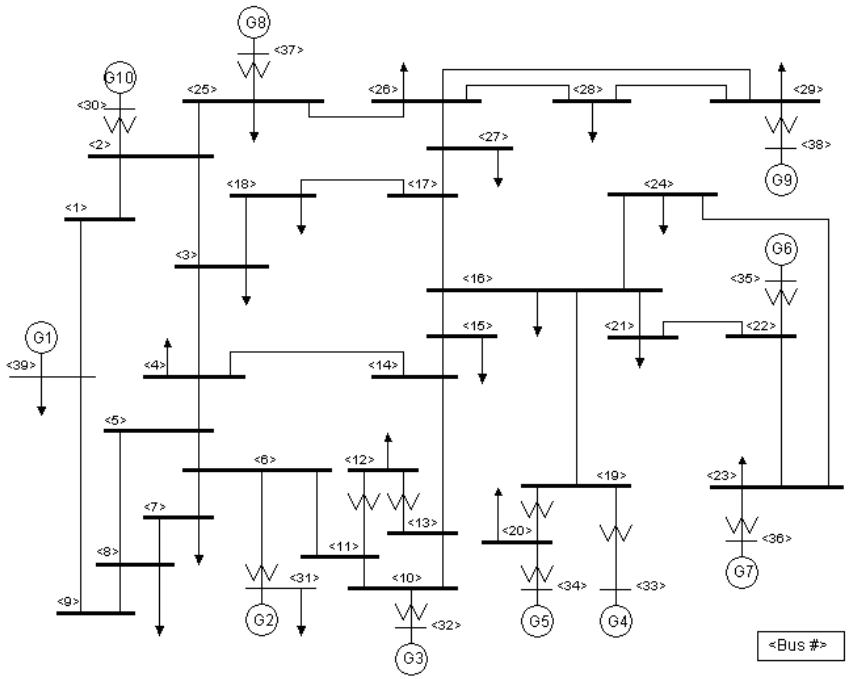
$\rightarrow$ disturbance rejection via **I-control**



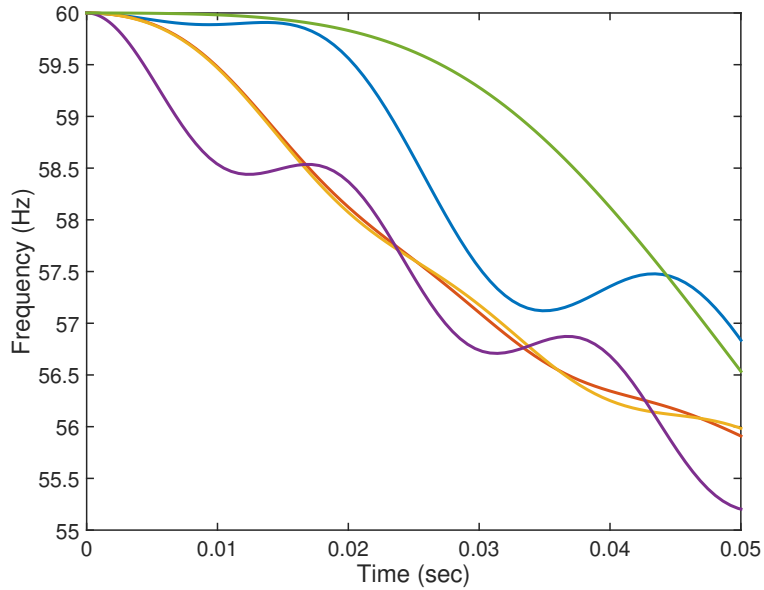
How many integrators?

(covered on the board)

Further robustness arguments supporting “at most one integrator”



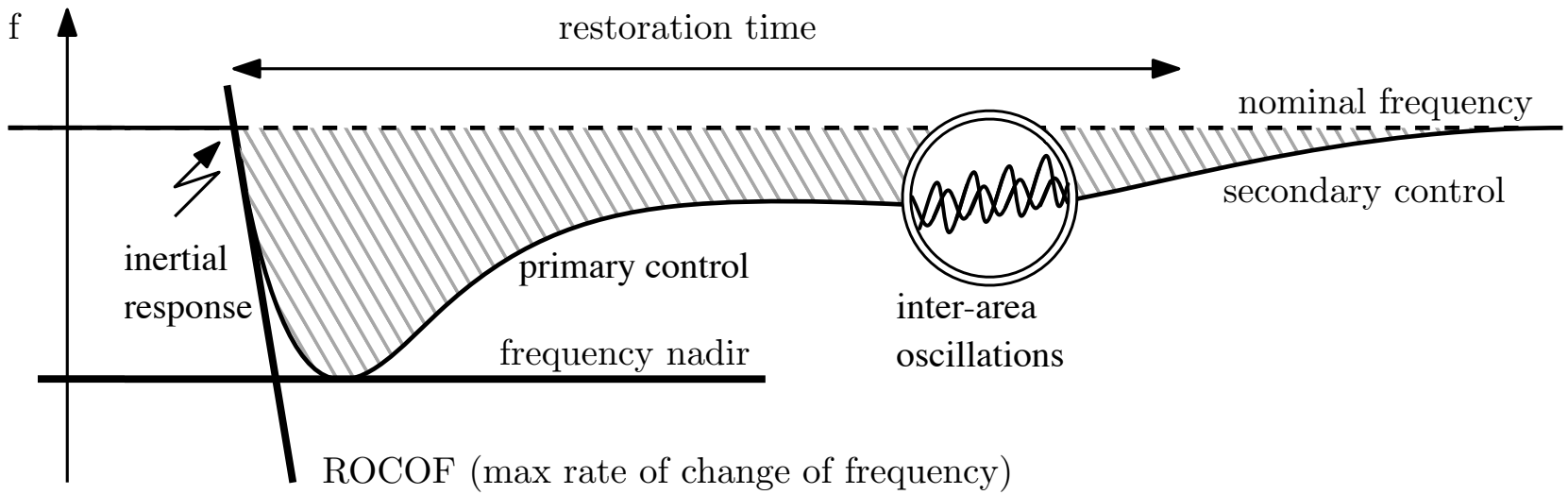
IEEE New England power grid



effect of $n > 1$ **decentralized secondary integral controllers** in presence of measurement errors

(covered on board)

Recall: fault response & control actions



1. **physical inertia** instantly provides decentralized **derivative** control
2. **decentralized primary** loops at devices provide **proportional** control
3. **system-wide secondary** loop provides centralized **integral** control

$\rightarrow$ another perspective on the swing equation

$$\underbrace{M\,\dot{\omega}}_{\text{D}} + \underbrace{K_{\text{primary}}(\omega - \omega_{\text{ref}})}_{\text{P}} + \underbrace{K_{\text{secondary}} \int_0^t (\omega - \omega_{\text{ref}})\, d\tau}_{\text{I}} = p(\theta) - \underbrace{p_{\text{ref}}}_{\text{set-point}}$$

Optimal secondary control

(covered on the board)

#2 control objective: optimality

optimization objective

$$\text{minimize}_u \quad \sum_i J_i(u_i)$$

$$\text{subject to} \quad \sum_i p_{i,\text{ref}} + u_i = 0$$

- generation limits $u_i \in \mathcal{U}_i = [\underline{u}_i, \overline{u}_i]$ absorbed in differentiable cost
- neglected: ramping, network, area balance constraints, ...

optimality condition $\boxed{\exists\, \eta \text{ s.t. } \nabla J_i(u_i) = \eta}$ to be enforced by controllers

1. **gather & broadcast** approach

$$\underbrace{\tau\, \dot{\eta} \;=\; -\Delta\omega}$$

central integral action based on global $\Delta\omega$

$$\underbrace{u_i \;=\; (\nabla J_i)^{-1}(\eta)}$$

decentralized allocation rule

2. **distributed control** approach

$$\underbrace{\tau_i\, \dot{\eta}_i \;=\; -\Delta\omega_i - \sum_j a_{ij}(\eta_i - \eta_j)}$$

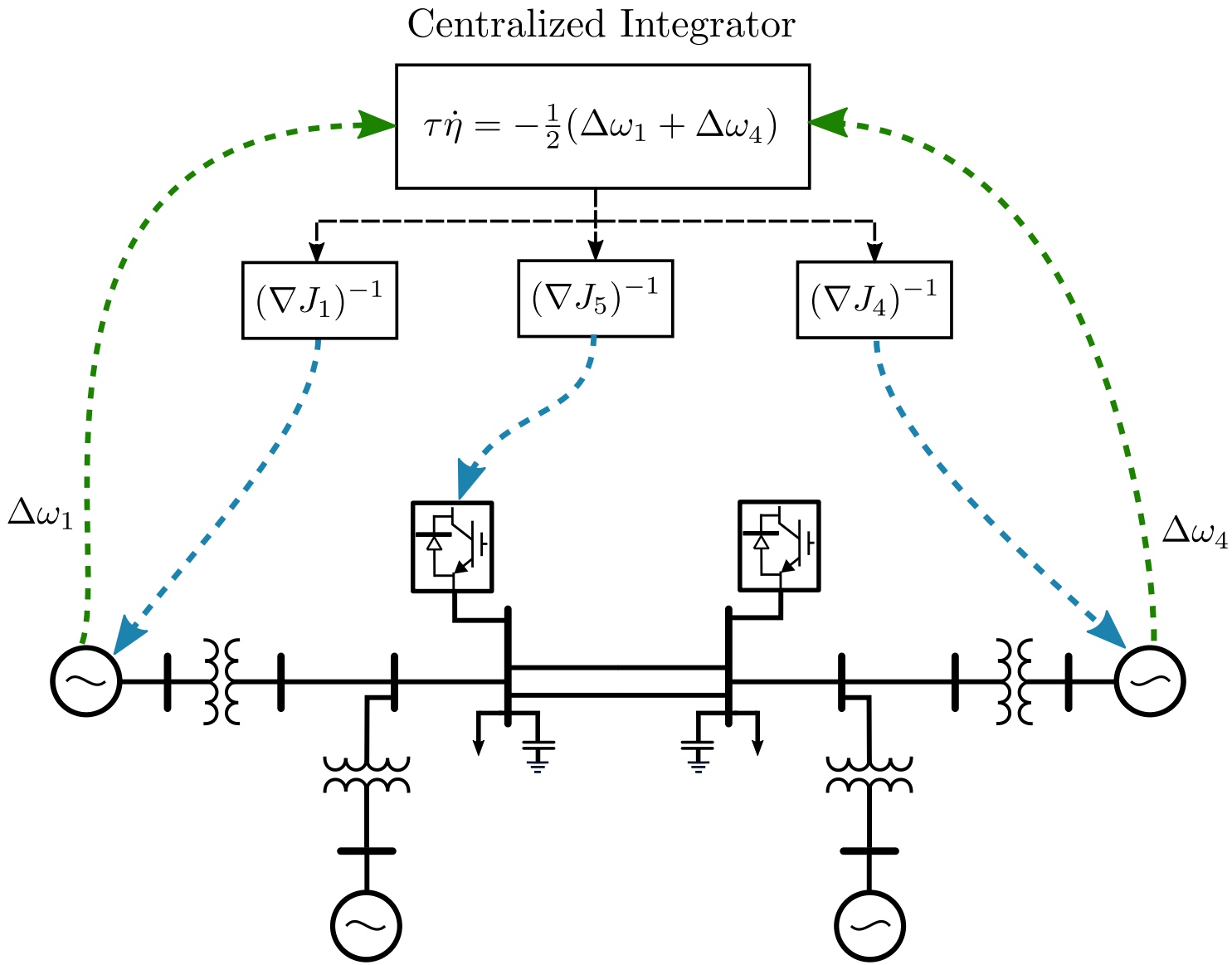
distributed integral action (e.g., consensus)

$$\underbrace{u_i \;=\; (\nabla J_i)^{-1}(\eta)}$$

decentralized allocation rule

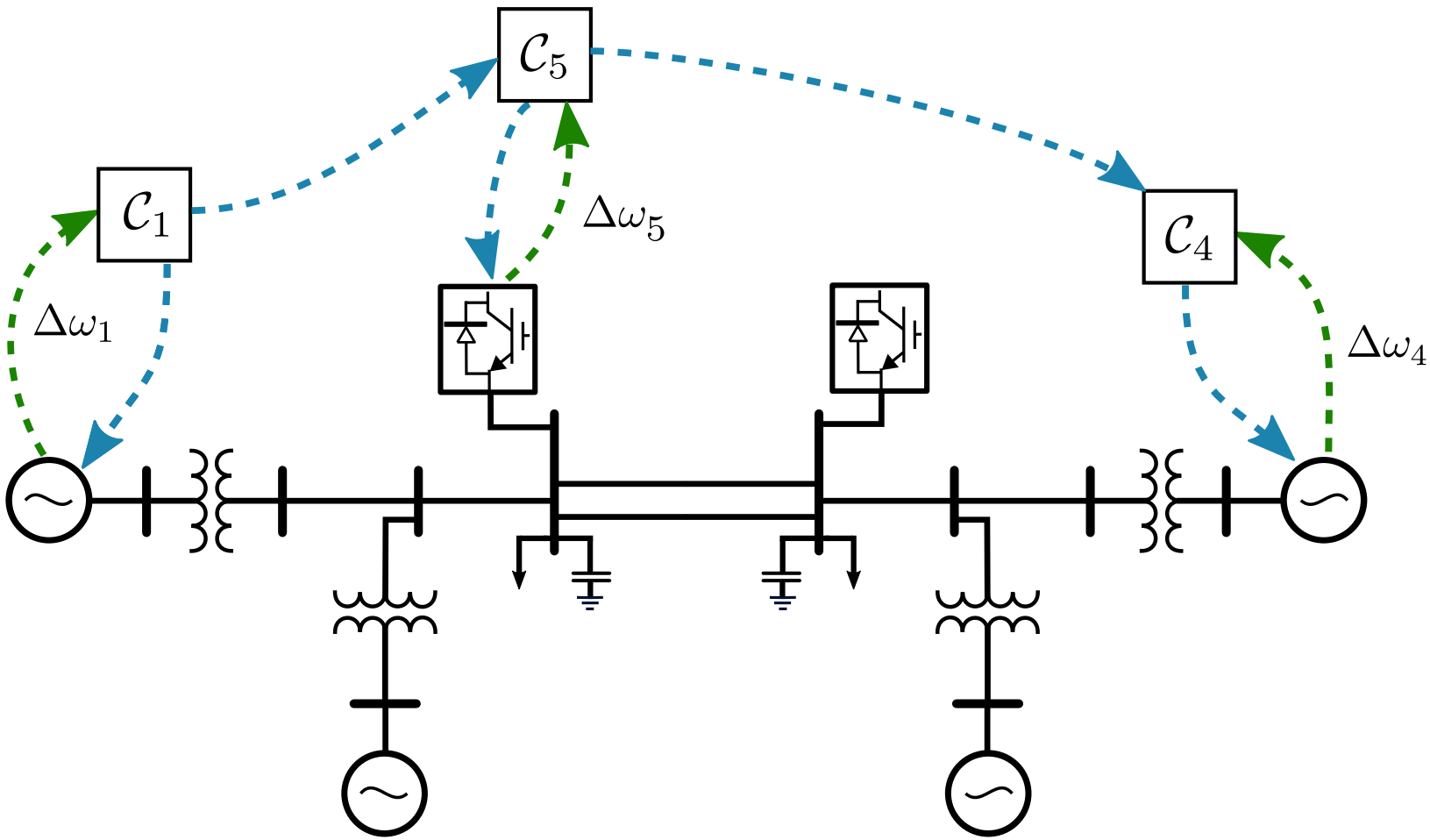
Prototypical gather & broadcast architecture

(figure adapted from John Simpson-Porco)



Prototypical distributed control architecture

(figure adapted from John Simpson-Porco)



real-world automatic generation control (AGC) requires further ingredients

#3 further important real-world objectives that we sweep under the carpet today

- **ACE** area control error = { frequency error } + { generation - load - tie-line flow }

$\frac{1}{s}$ **centralized integral control**

$$\tau\,\dot{\eta}(t) = \text{ACE}$$

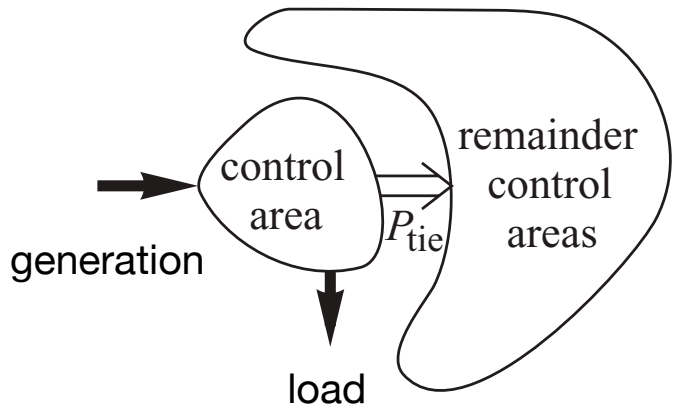
- **generation allocation**

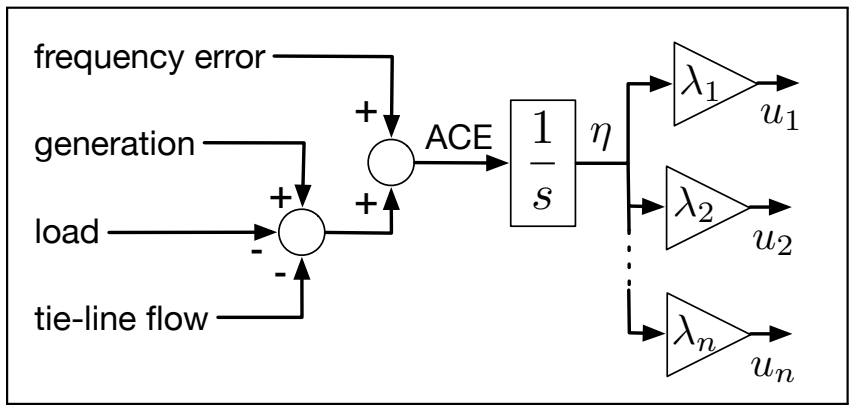
  $u_i(t) = \lambda_i\,\eta(t)$, where λ_i is generation participation factor (e.g., $\lambda_i = -\frac{\partial}{\partial \eta}\left(\nabla J_i\right)^{-1}(\eta)$)

- **implementation** subject to dead-band & saturation & often with proportional control action

- detailed dynamics: turbine dynamics, losses, voltages, ...

- further engineering issues ...





AGC implementation

A few theory references a little closer to practice . . . everything can be extended

Reexamining the Distributed Slack Bus

Sairaj V. Dhople, *Member, IEEE*, Yu Christine Chen, *Member, IEEE*,
Abdullah Al-Digs, *Student Member, IEEE*, and Alejandro Domínguez-García, *Senior Member, IEEE*

On Area Control Errors, Area Injection Errors, and Textbook Automatic Generation Control

John W. Simpson-Porco, *Member, IEEE*

A Dynamic Stability and Performance Analysis of Automatic Generation Control

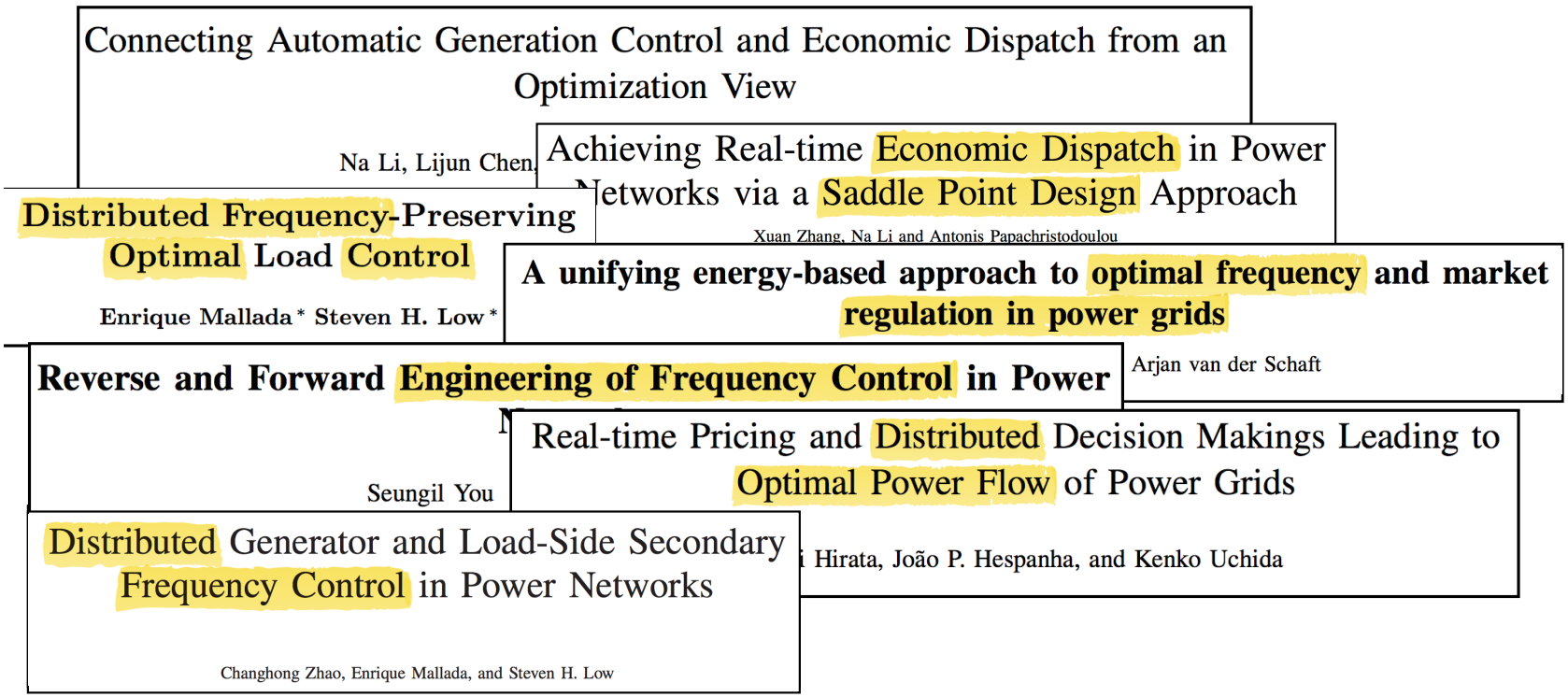
John W. Simpson-Porco, *Member, IEEE*

Energy-based analysis and control of power networks and markets

Port-Hamiltonian modeling, optimality and game theory

Outline

A plethora of algorithms have emerged . . .



common theme: optimization algorithms as distributed feedback controllers

See recent surveys for (partial) overview

A Survey of Distributed Optimization and Control Algorithms for Electric Power Systems

Daniel K. Molzahn,* *Member, IEEE*, Florian Dörfler,† *Member, IEEE*, Henrik Sandberg,‡ *Member, IEEE*, Steven H. Low,§ *Fellow, IEEE*, Sambuddha Chakrabarti,¶ *Student Member, IEEE*, Ross Baldick,¶ *Fellow, IEEE*, and Javad Lavaei,** *Member, IEEE*

On the Secondary Control Architectures of AC Microgrids: An Overview

Yousef Khayat, Qobad Shafiee, *Senior Member, IEEE,* Rasool Heydari, Mobin Naderi, Tomislav Dragicevic, *Senior Member, IEEE,* John W. Simpson-Porco, *Member, IEEE,* Florian Dörfler, *Member, IEEE,* Mohammad Fathi, Frede Blaabjerg, *Fellow, IEEE*, Josep M. Guerrero, *Fellow, IEEE*, and Hassan Bevrani, *Senior Member, IEEE*

. . . see Stegink, Andreasson, Tegling, Mallada, Simpson-Porco, . . .

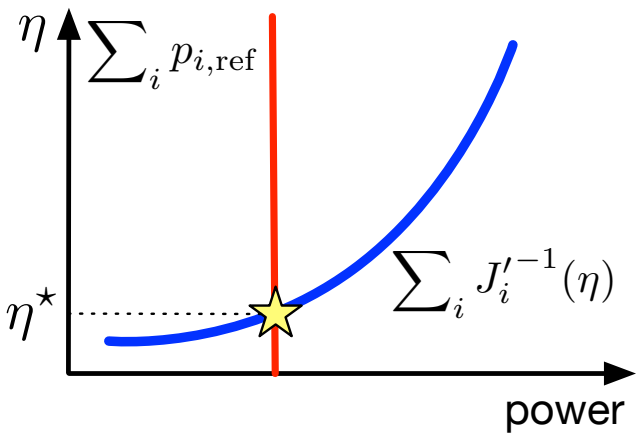
$\sim$ **3 categories** : primal-dual methods, distributed consensus-based averaging, gather & broadcast (including AGC)

Motivation: from social welfare to competitive markets

social welfare dispatch

$$\min_{u} \sum_i J_i(u_i)$$

$$\text{s.t.} \sum_i p_{i,\text{ref}} + u_i = 0$$



local (!) $\Longrightarrow$

measurable (!) $\Longrightarrow$

competitive spot market

1. given a prize η, player i **bids**

$$u_i^\star = \arg\min_{u_i \in \mathcal{U}_i} \{J_i(u_i) - \eta u_i\} = (\nabla J_i)^{-1}(\eta)$$

2. **market clearing** prize $\eta^\star$ from

$$0 = \sum_i P_i + u_i^\star = \sum_i p_{i,\text{ref}} + (\nabla J_i)^{-1}(\eta^\star)$$

auction (dual ascent)

1. local **best response** for given prize:

$$u_i^+ = \arg\min_{u_i \in \mathcal{U}_i} \{J_i(u_i) - \eta u_i\} = (\nabla J_i)^{-1}(\eta)$$

2. update prize of **constraint violation**:

$$\eta^+ = \eta - \epsilon \left(\sum_i p_{i,\text{ref}} + u_i^+\right) = \eta - \tilde{\epsilon} \cdot \omega_{\text{sync}}$$

now we take the continuous limit $\epsilon \to 0$

Gather & broadcast control

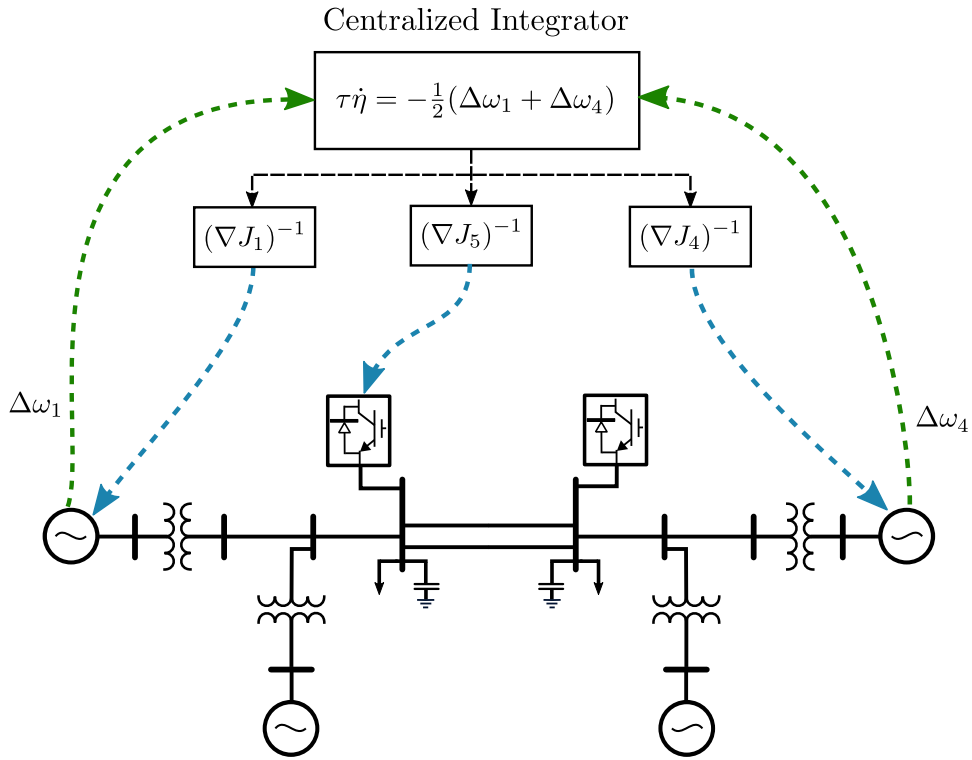
1. η = **aggregate integral** of averaged measurements

$$k\,\dot{\eta} = -\sum_i C_i\,\Delta\omega_i$$

where $C_i \geq 0$ and $k > 0$

2. u_i = **local best response**

$$u_i = (\nabla J_i)^{-1}(\eta)$$



special case is automatic generation control **AGC**:

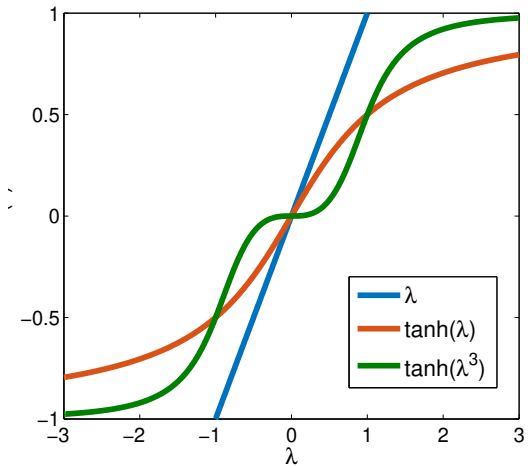
- single frequency measurement $C_i = \begin{cases} 1 & \text{if } i = i^* \\ 0 & \text{otherwise} \end{cases}$
- quadratic cost $J_i(u_i) = \frac{1}{2}a_i u_i^2 \quad \rightarrow \quad u_i = (\nabla J_i)^{-1}(\eta) = \underbrace{\frac{1}{a_i}}_{\text{participation factor}} \eta_i$

Effect of cost function on control allocation

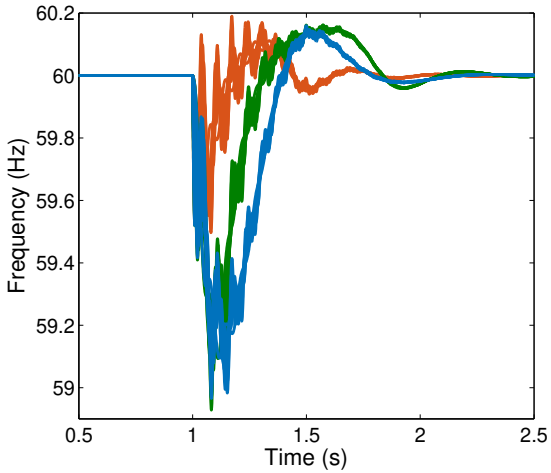
(covered on the board)

Effect of nonlinear frequency response curves

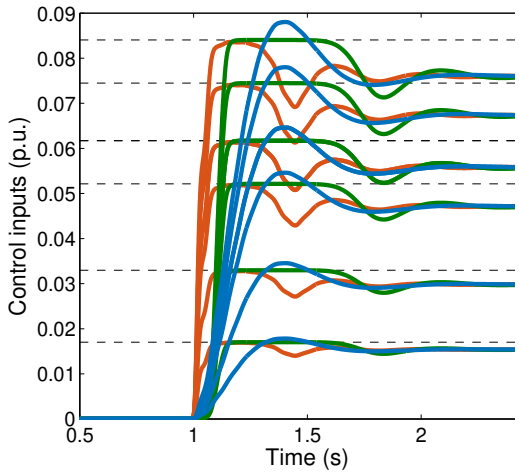
case study: IEEE 39 New England system



optimal local frequency response curves $J'^{-1}(\eta)$



gather-and-broadcast closed-loop frequencies



gather-and-broadcast control inputs

Closed-loop stability analysis

(covered on the board)

Details & initial condition for further reading

Analysis and Synthesis of Low-Gain Integral Controllers for Nonlinear Systems with Application to Feedback-Based Optimization

John W. Simpson-Porco, *Member, IEEE*

Gather-and-broadcast frequency control in power systems☆

Florian Dörfler [a], Sergio Grammatico [b]

[a] *Automatic Control Laboratory, Swiss Federal Institute of Technology (ETH) Zürich, 8092, Switzerland*

[b] *Department of Electrical Engineering, Eindhoven University of Technology, 5612 AJ, The Netherlands*

Distributed control of power networks

Passivity, optimality and energy functions

Distributed averaging-based integral control

also known as DAI, DAPI, distributed integral action, consensus filter, ...

recall **optimality condition** $\boxed{\exists\, \eta \text{ s.t. } \nabla J_i(u_i) = \eta}$ as starting point for design

recall **distributed averaging** $\dot{\eta}_i = \sum_j a_{ij}(\eta_i - \eta_j) \overset{t\to\infty}{\longrightarrow} \{\eta_i = \eta_j \ \forall i, j\}$

distributed averaging integral control approach:

$$\underbrace{\tau_i \dot{\eta}_i = -k_i \Delta\omega_i - \sum_j a_{ij}(\eta_i - \eta_j)}_{\text{distributed integral action}} \qquad \underbrace{u_i = (\nabla J_i)^{-1}(\eta)}_{\text{decentralized allocation rule}}$$

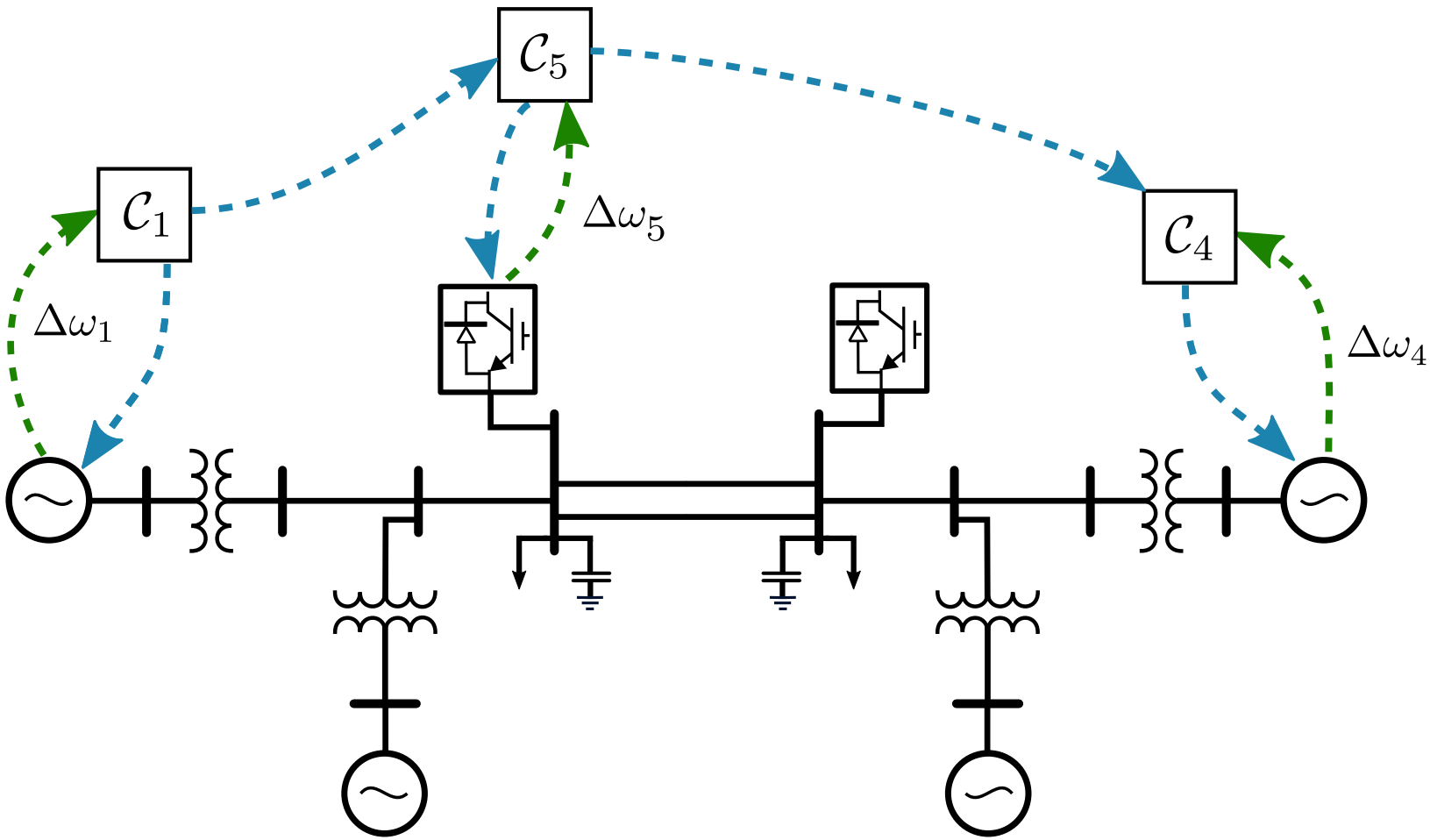
$=$ distributed averaging of marginal costs $\eta_i = \nabla J_i(u_i)$ $\sim$ optimality

$+$ integration of average frequency $\frac{d}{dt}\sum_i \tau_i \eta_i = \sum_i k_i \Delta\omega_i$ $\sim$ balance

$+$ decentralized allocation as in gather & broadcast

Distributed averaging-based integral control

(figure adapted from John Simpson-Porco)



Closed-loop stability analysis

(covered on the board)

Details & initial condition for further reading

a lot(!) of work has been done on this topic

Distributed vs. Centralized Power Systems Frequency Control

Martin Andreasson[1,2] , Dimos V. Dimarogonas[1], Karl H. Johansson[1] and Henrik Sandberg[1]
*ACCESS Linnaeus Center, KTH Royal Institute of Technology, Stockholm, Sweden.

Distributed control of power networks

Passivity, optimality and energy functions

On Stability of Distributed-Averaging Proportional-Integral Frequency Control in Power Systems

John W. Simpson-Porco

A Survey of Distributed Optimization and Control Algorithms for Electric Power Systems

Daniel K. Molzahn,* *Member, IEEE*, Florian Dörfler,† *Member, IEEE*, Henrik Sandberg,‡ *Member, IEEE*, Steven H. Low,§ *Fellow, IEEE*, Sambuddha Chakrabarti,¶ *Student Member, IEEE*, Ross Baldick,¶ *Fellow, IEEE*, and Javad Lavaei,** *Member, IEEE*

Stability and Optimality of Distributed Secondary Frequency Control Schemes in Power Networks

Andreas Kasis, Nima Monshizadeh, Eoin Devane, and Ioannis Lestas

Synchronization and power sharing for droop-controlled inverters in islanded microgrids☆

John W. Simpson-Porco [1], Florian Dörfler, Francesco Bullo
Center for Control, Dynamical Systems, and Computation, University of California, Santa Barbara, CA 93106, USA

A Lyapunov approach to control of microgrids with a network-preserved differential-algebraic model

Claudio De Persis Nima Monshizadeh Johannes Schiffer Florian Dörfler

On the Secondary Control Architectures of AC Microgrids: An Overview

Yousef Khayat, Qobad Shafiee, *Senior Member, IEEE,* Rasool Heydari, Mobin Naderi, Tomislav Dragicevic, *Senior Member, IEEE,* John W. Simpson-Porco, *Member, IEEE,* Florian Dörfler, *Member, IEEE,* Mohammad Fathi, Frede Blaabjerg, *Fellow, IEEE*, Josep M. Guerrero, *Fellow, IEEE*, and Hassan Bevrani, *Senior Member, IEEE*

Energy-based analysis and control of power networks and markets

Port-Hamiltonian modeling, optimality and game theory

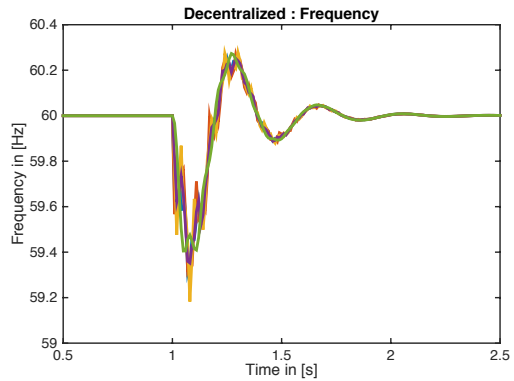
Robustness of distributed averaging control in power systems: Time delays & dynamic communication topology☆

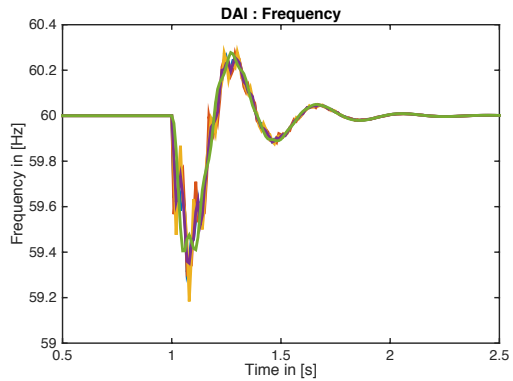
Johannes Schiffer [a], Florian Dörfler [b], Emilia Fridman [c,d]

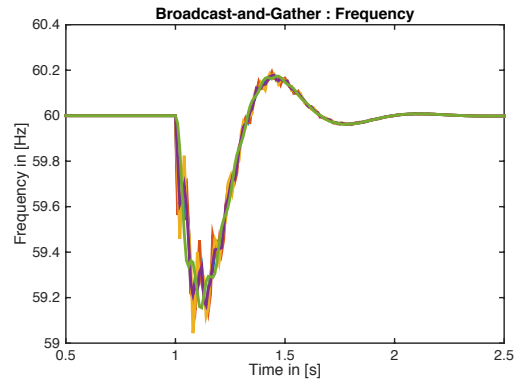
[a] *School of Electronic & Electrical Engineering, University of Leeds, LS2 9JT, United Kingdom*
[b] *Automatic Control Laboratory, Swiss Federal Institute of Technology (ETH) Zürich, 8092, Switzerland*
[c] *Tel Aviv University, Tel Aviv 69978, Israel*
[d] *ITMO University, 49 Avenue Kronverkskiy, 197101 Saint Petersburg, Russia*

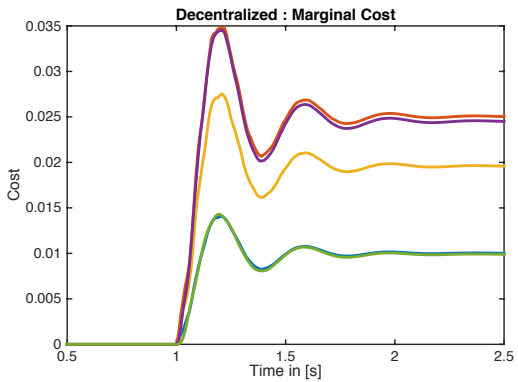
Comparison of different control strategies

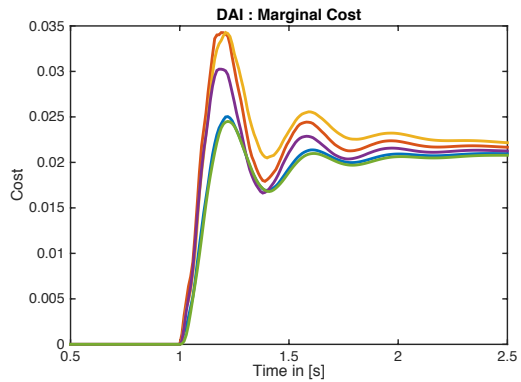
case study: IEEE 39 New England system

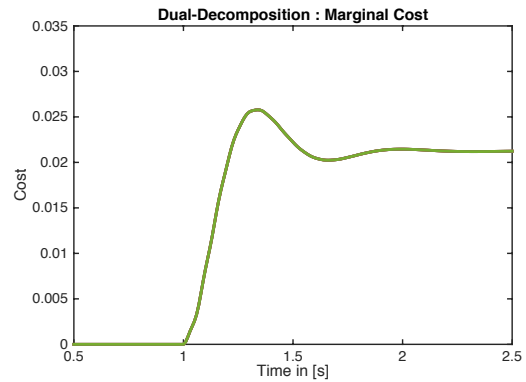












(idealized) decentralized integral control

distributed averaging integral (DAI) control

gather-and-broadcast integral control

gather-and-broadcast is comparable to DAI with much less communication

Primal dual control approaches

(covered on the board)

Details & initial condition for further reading

Design and Stability of Load-Side Primary Frequency Control in Power Systems

Changhong Zhao, *Student Member, IEEE*, Ufuk Topcu, *Member, IEEE*, Na Li, *Member, IEEE*, and Steven Low, *Fellow, IEEE*

A real-time control framework for smart power networks: Design methodology and stability☆

Xuan Zhang [1], Antonis Papachristodoulou

Department of Engineering Science, University of Oxford, Parks Road, Oxford, OX1 3PJ, United Kingdom

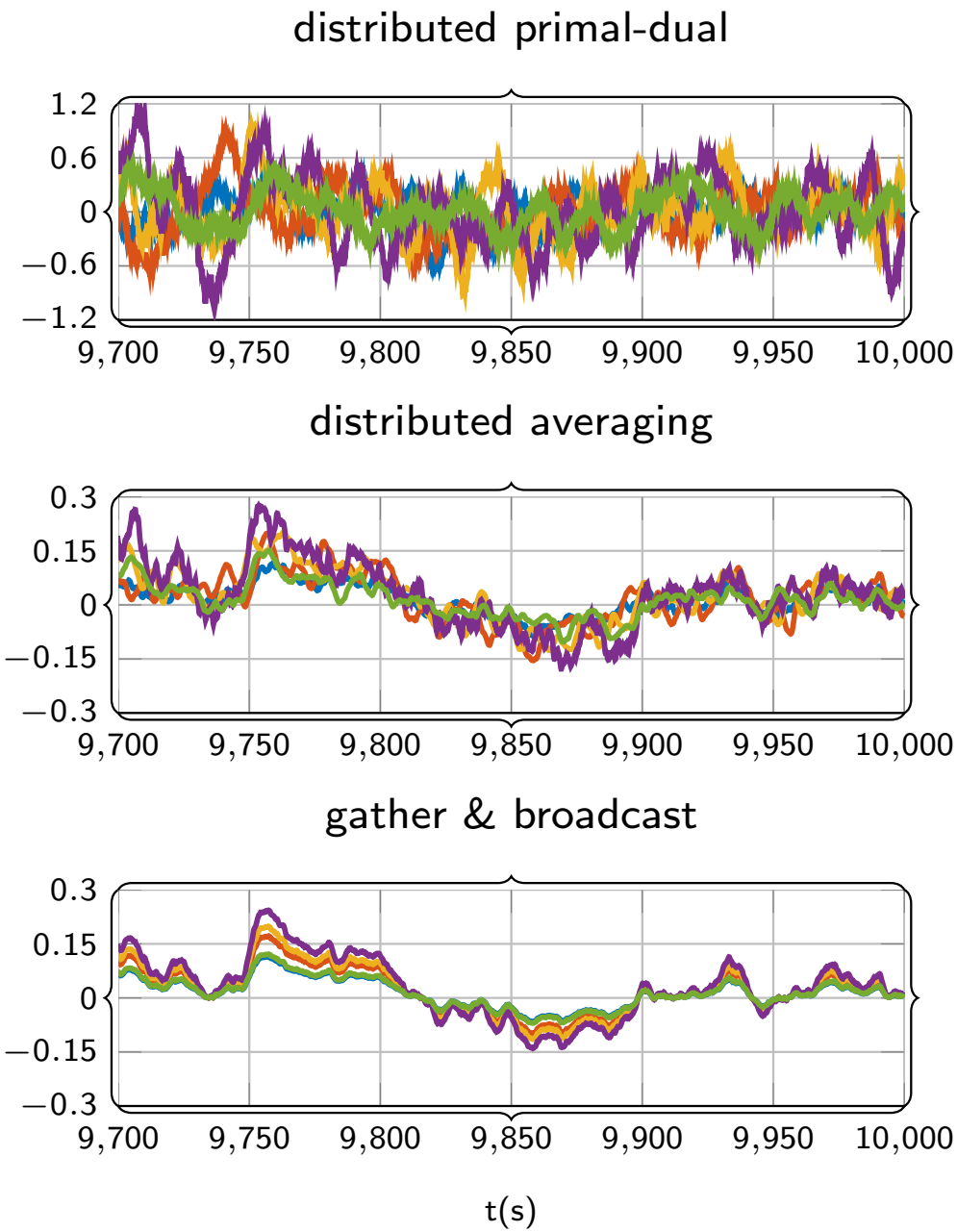
Connecting Automatic Generation Control and Economic Dispatch From an Optimization View

Na Li, *Member, IEEE*, Changhong Zhao, *Member, IEEE*, and Lijun Chen, *Member, IEEE*

Optimal Load-Side Control for Frequency Regulation in Smart Grids

Enrique Mallada, *Member, IEEE*, Changhong Zhao, *Member, IEEE*, and Steven Low, *Fellow, IEEE*

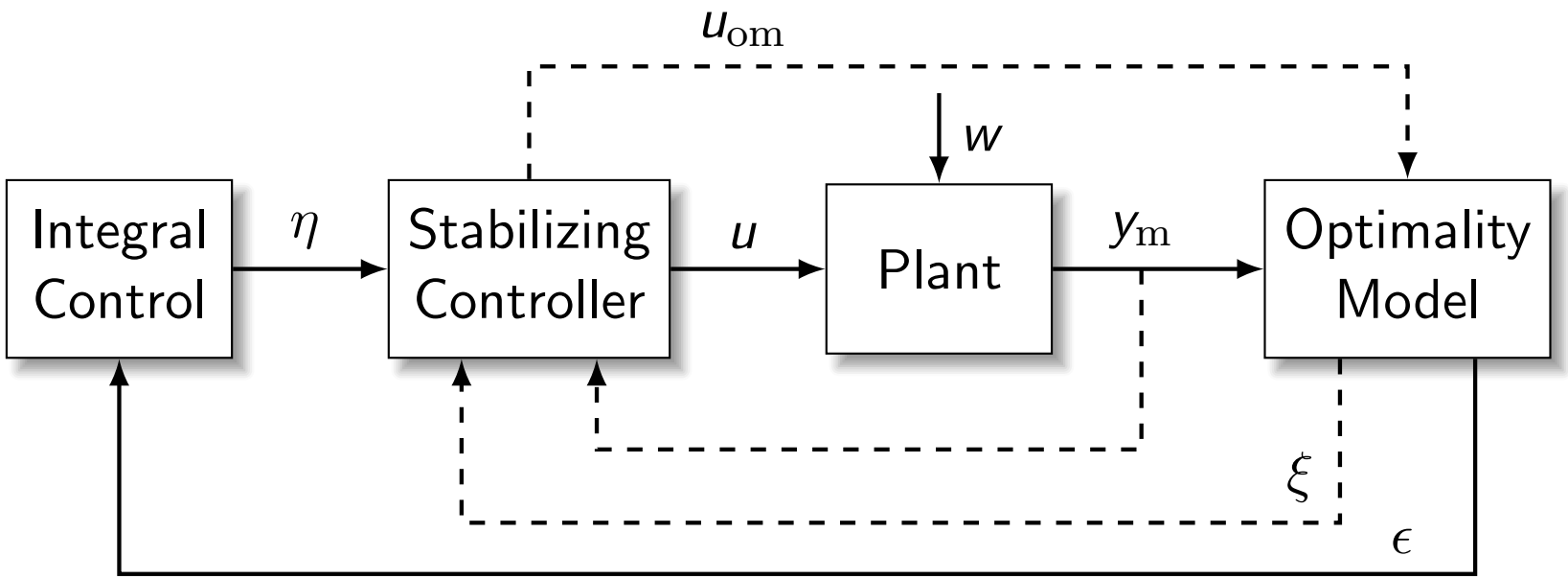
Comparison studies



- synthetic test case ($n = 5$), acyclic, heterogeneous, & excitation via white noise
- plots show control costs $J_i(u_i)$ (similar plots for frequencies ω_i)
- distributed primal-dual has worst variance & performs even worse when adding ω feedback
- similar performance of distributed averaging & gather & broadcast
- results supported by analytic $\mathcal{H}_2$-norm calculations; see *"Quadratic Performance Analysis of Secondary Frequency Controllers"* by Poolla et al.

Unifying optimal steady-state control

L. Lawrence, JWSP, E. Mallada “Linear-convex optimal steady-state control”



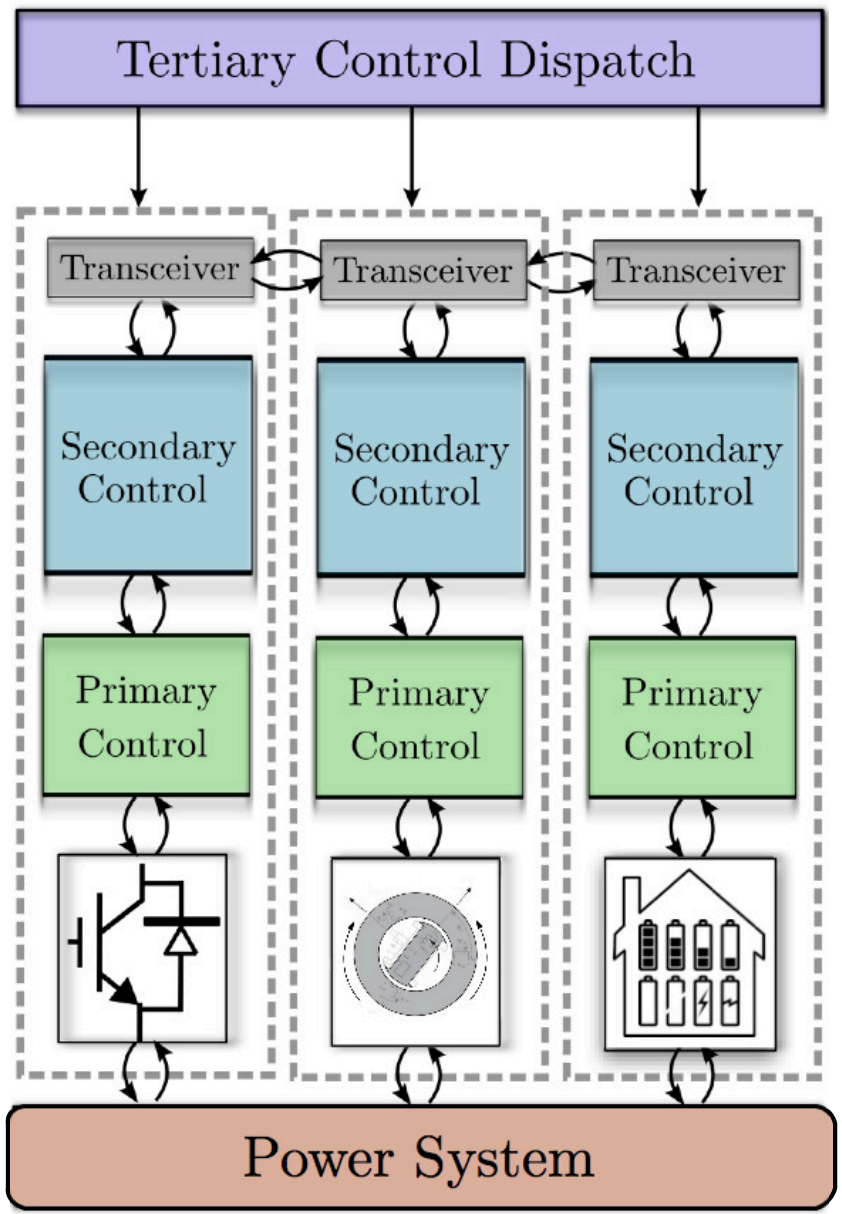
- **optimality model** creates error signal ϵ (e.g., mismatch in marginal costs)
- **integral control** integrates error ϵ (e.g., distributed averaging-based PI)
- **stabilizing controller** stabilizes closed-loop system (plant + optimization)

Outline

note: microgrids are much simpler than power systems & slightly hypothetical

$\rightarrow$ everything is open game

Conventional power systems control hierarchy



3. **Tertiary control** (offline)
   - goal: optimize operation
   - architecture: centralized & forecast
   - strategy: scheduling (OPF)

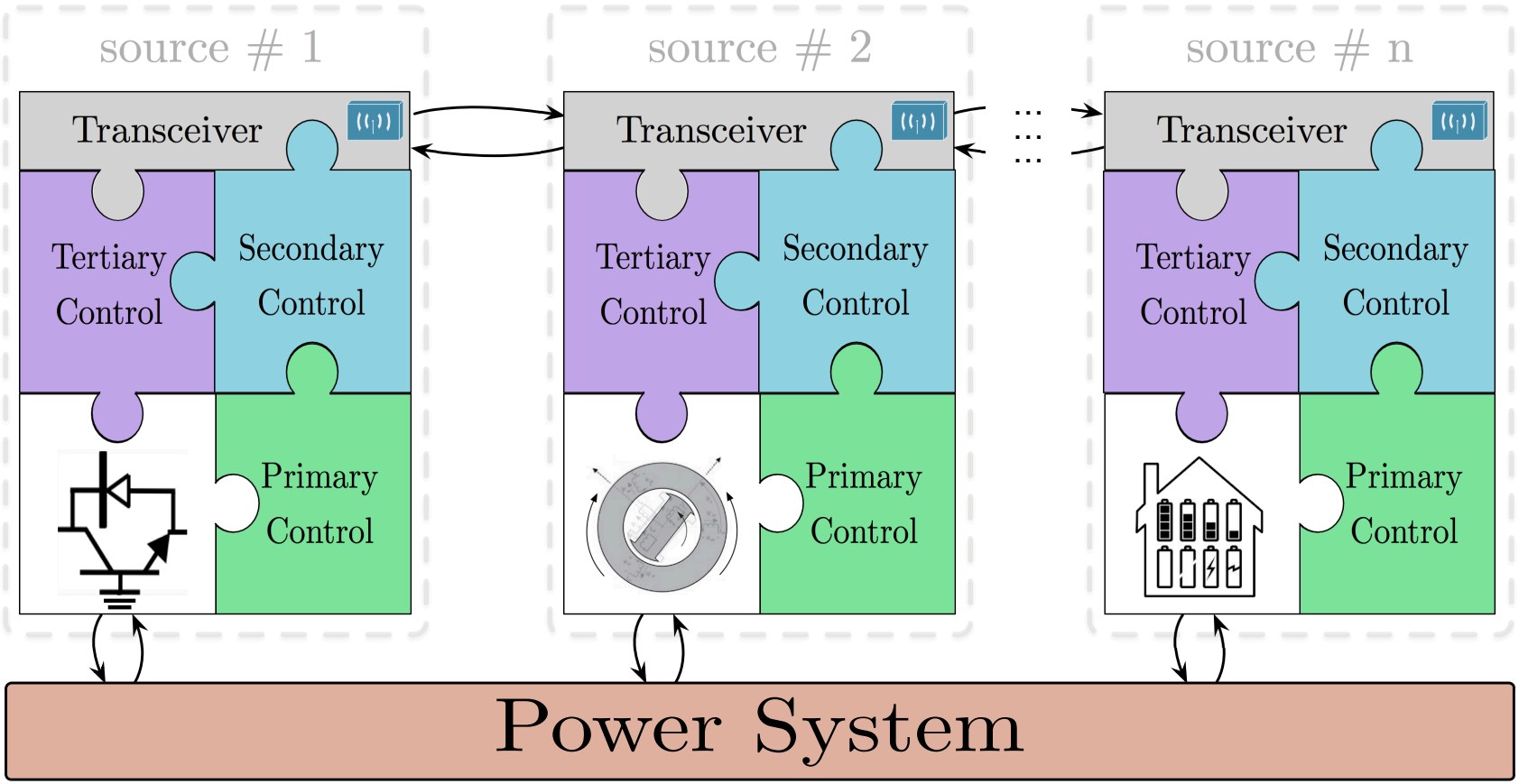
2. **Secondary control** (slower)
   - goal: maintain operating point
   - architecture: centralized
   - strategy: I-control (AGC)

1. **Primary control** (fast)
   - goal: stabilization & load sharing
   - architecture: decentralized
   - strategy: P-control (droop)

Is this **top-to-bottom architecture** from conventional transmission grids appropriate in tomorrow's microgrids ?

Plug'n'play architecture

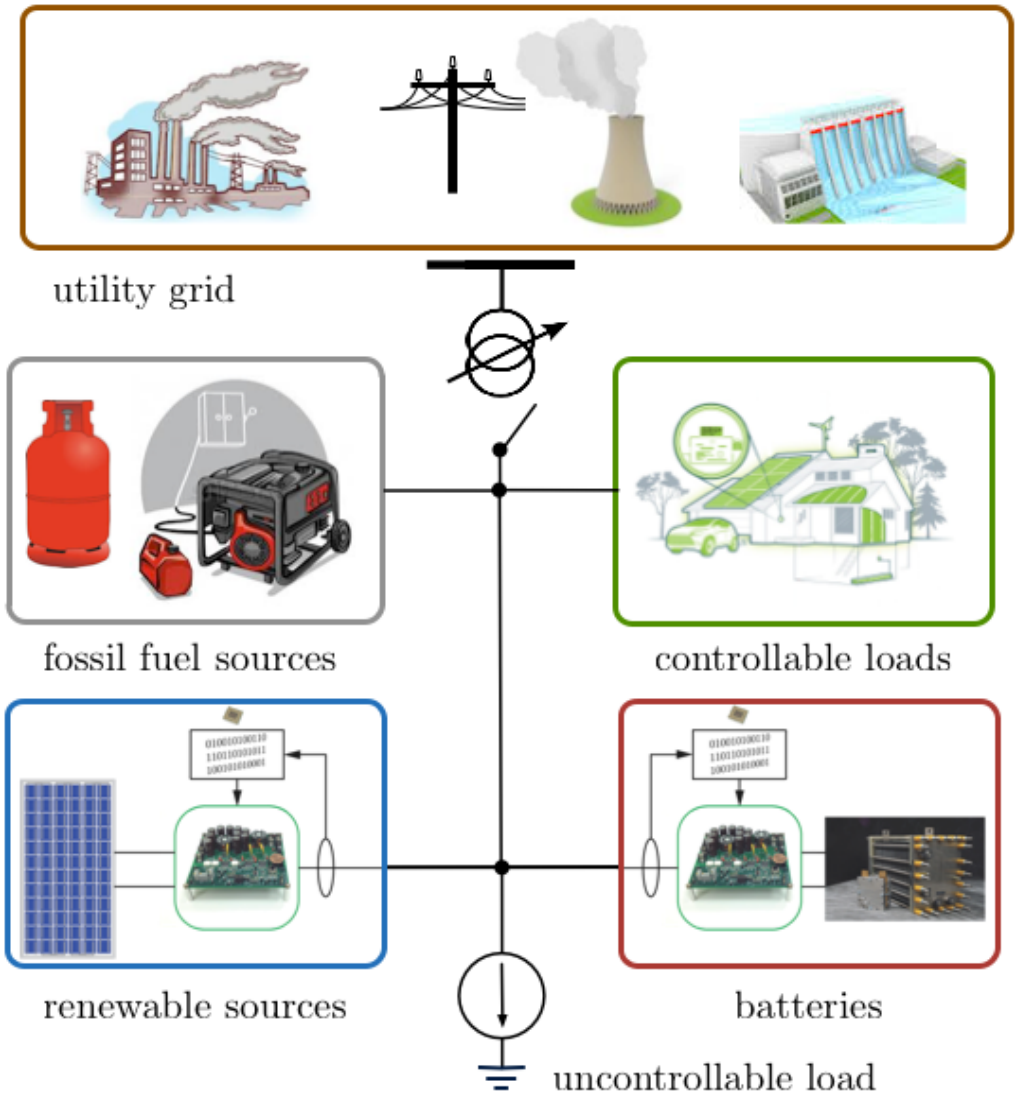
flat hierarchy, distributed, no time-scale separations, & model-free



approach from an optimal energy routing perspective

Energy management

as offline resource allocation & scheduling problem



Energy management

as offline resource allocation & scheduling problem



minimize {cost of generation, losses, . . . }

subject to

physical constraints:

equality constraints: power balance equations

operational constraints:

inequality constraints: flow/injection/voltage constraints

logic constraints: commit generators yes/no

⋮



The optimal dispatch / balancing problem

dispatch generation: $\min_{u_i \in \mathcal{U}_i} \underbrace{\sum_i J_i(u_i)}_{\text{generation cost}}$ subject to $\underbrace{\sum_i p_{i,\text{ref}} + u_i = 0}_{\text{load = generation}}$

1. primal feasibility = imbalance: $\sum_i p^{i,\text{ref}} + u_i = 0 \sim \omega_{\text{sync}}$ (measurable)
2. identical marginal costs at optimality: $J_i'(u_i) = J_j'(u_j) \ \forall i, j$ (consensus)

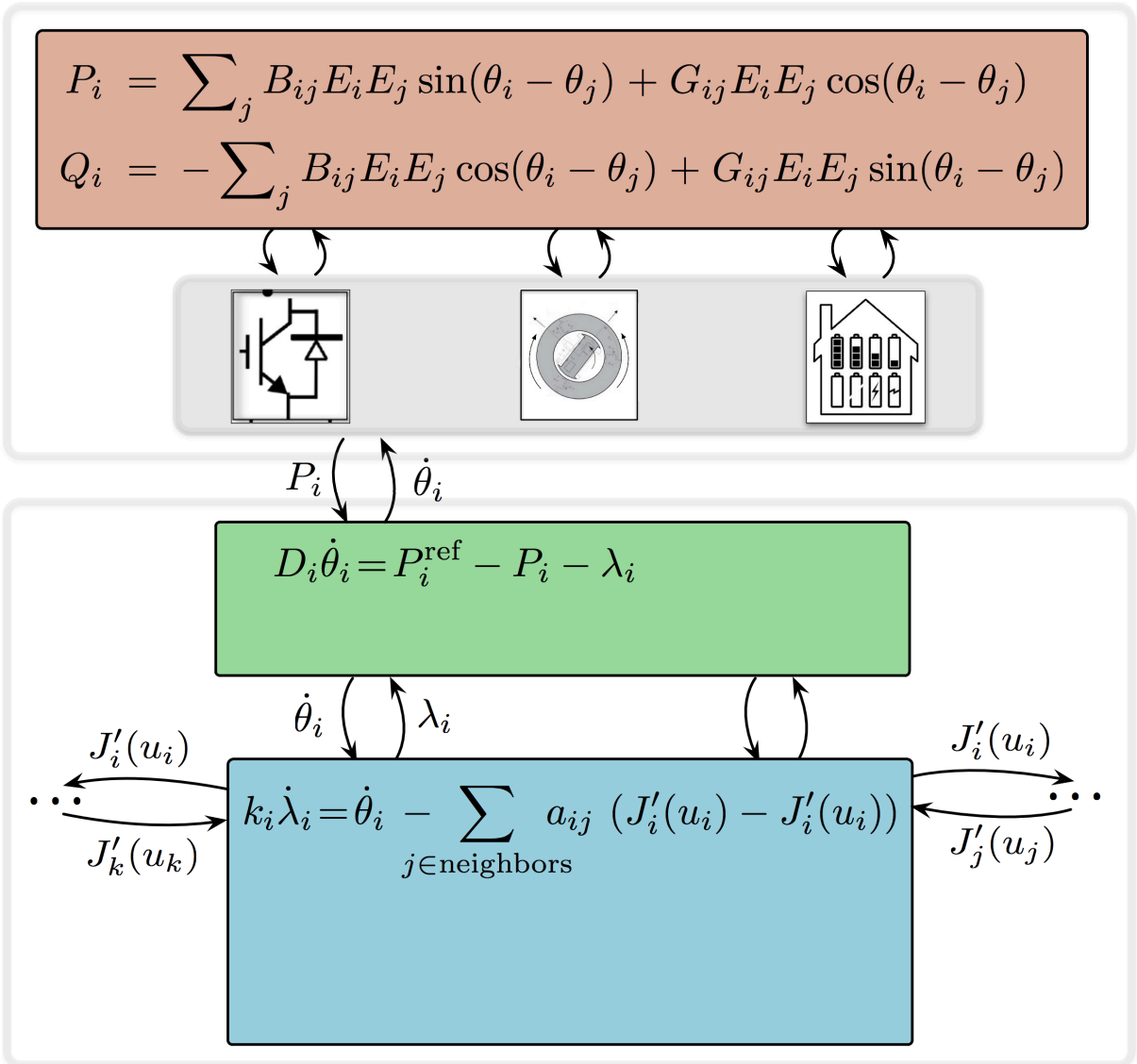
distributed averaging as seen from optimization algorithm perspective:

1. dual update on violation:
$$\lambda^+ = \lambda + \frac{1}{k} \cdot \omega_{\text{sync}}$$
2. consensus on $x_i = J_i'(u_i)$:
$$x_i^+ = x_i + \sum_{j \in \text{neighbors}} a_{ij} x_j$$

$\Rightarrow$ **altogether** in real-time: $\underbrace{k_i \dot{\lambda}_i = \dot{\theta}_i}_{\text{local dual update}} - \underbrace{\sum_{j \in \text{neighbors}} a_{ij} \left(J_i'(u_i) - J_i'(u_i) \right)}_{\text{distributed consensus (comm-based)}}$

$\Rightarrow$ **inject** $u_i(t) = \lambda_i(t)$

Plug'n'play architecture



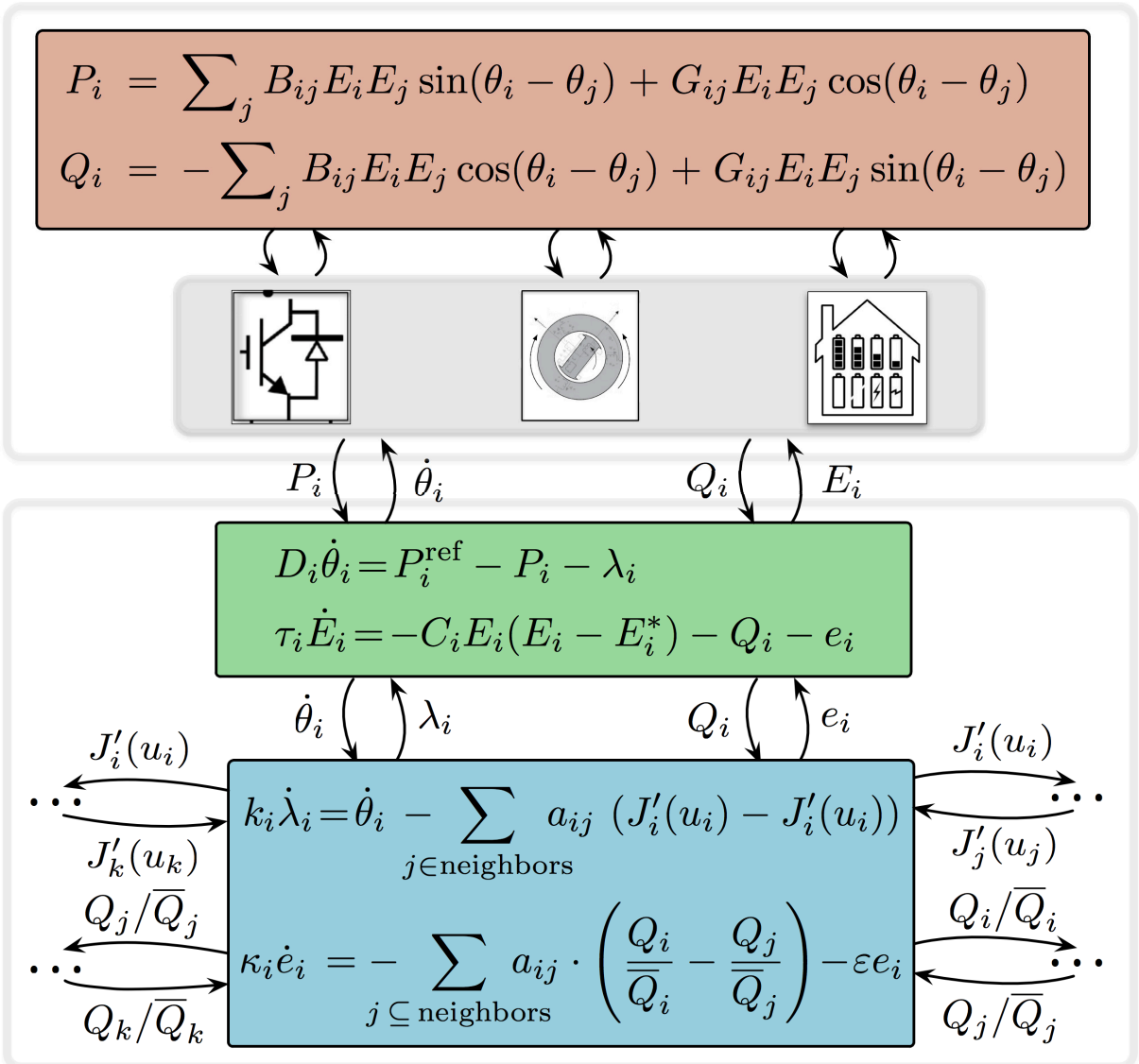
power system physics:
power flow
& devices

droop control:
trade off
power injections
& frequency

secondary & tertiary control:
integral errors &
diffusive averaging

Plug'n'play architecture

similar control strategies for voltage magnitude



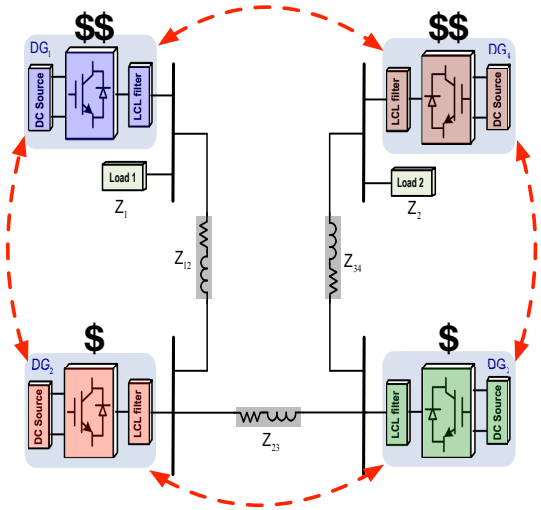
power system physics: power flow & devices

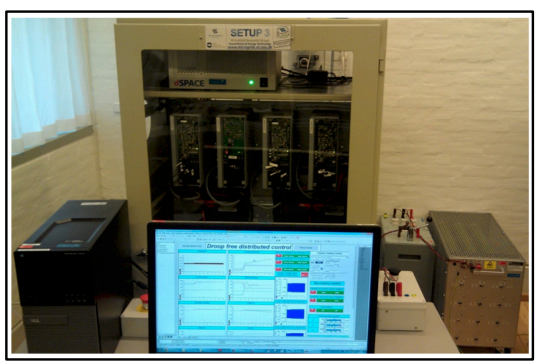
droop control: trade off power injections & frequency or voltage

secondary & tertiary control: integral errors & diffusive averaging

Experimental validation

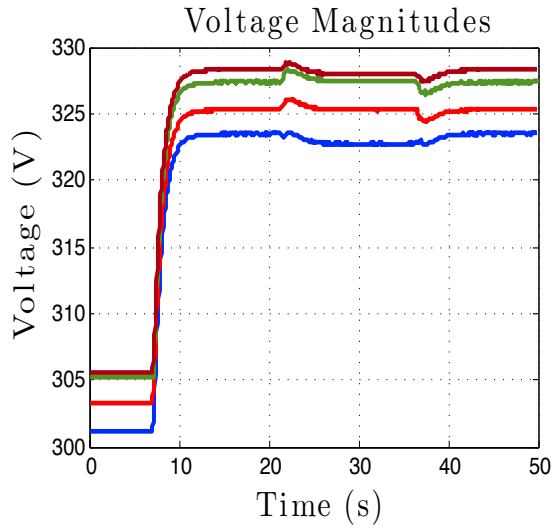
in collaboration with Q. Shafiee & J.M. Guerrero @ Aalborg University

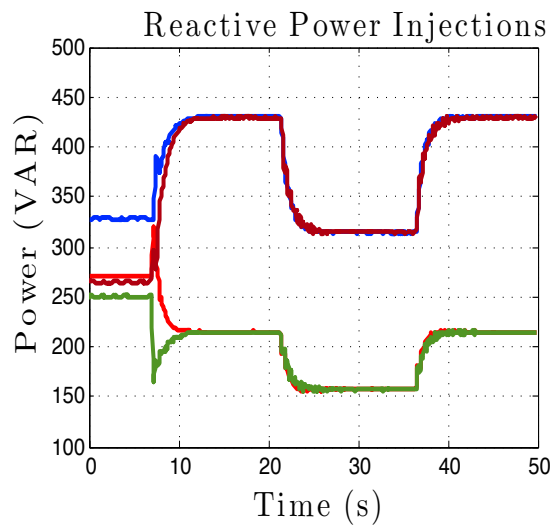


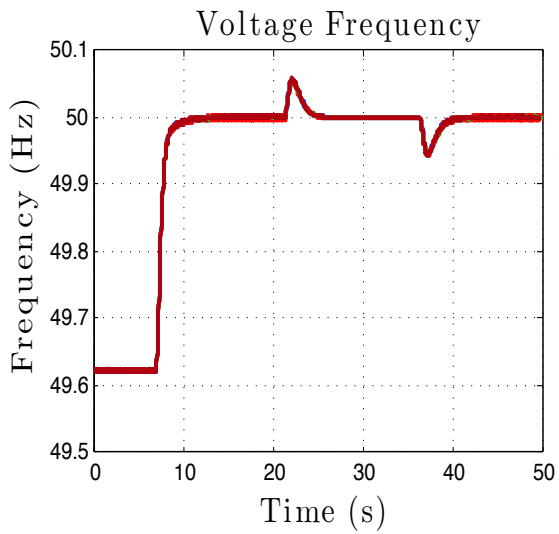


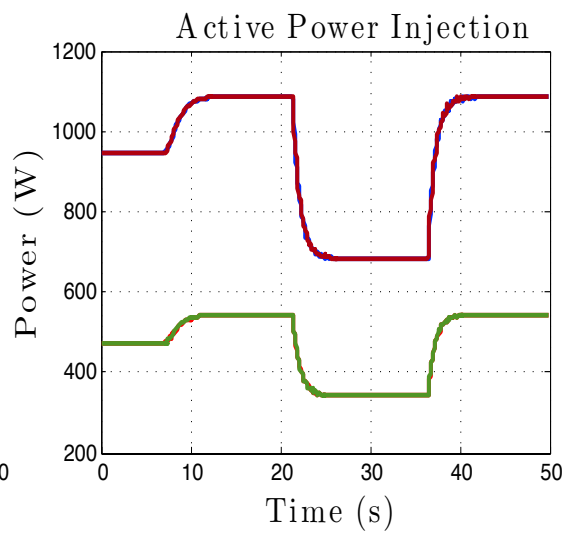
$t = 22s$: load # 2 unplugged

$t = 36s$: load # 2 plugged back









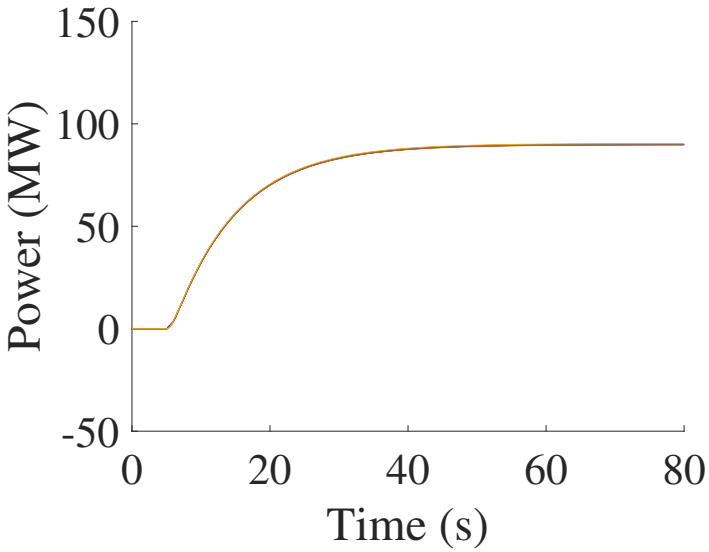
Outline

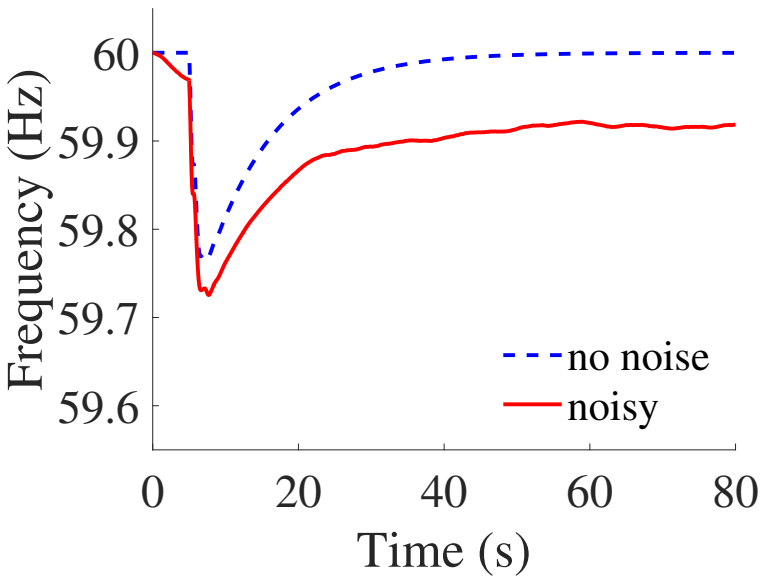
Recall: decentralized integral control

fully decentralized integral control

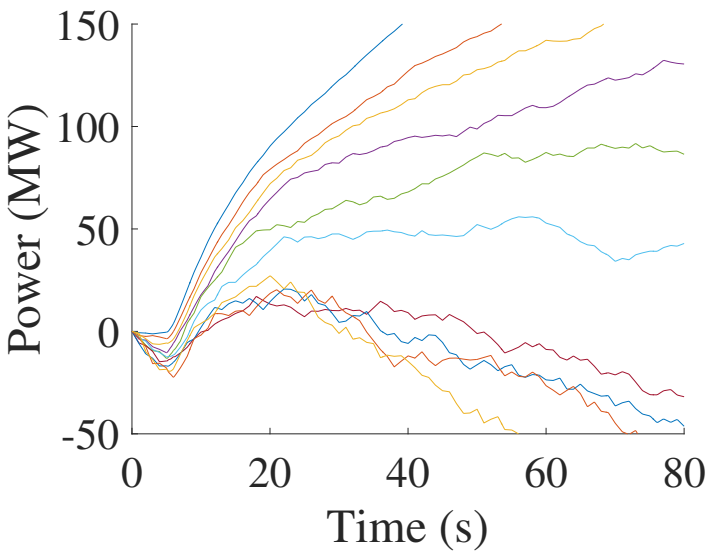
$$\tau_i \dot{\eta}_i = -\Delta\omega_i$$
$$u_i = (\nabla J_i)^{-1}(\eta)$$

discarded due to **lack of robustness**





↑ no noise noise ↓



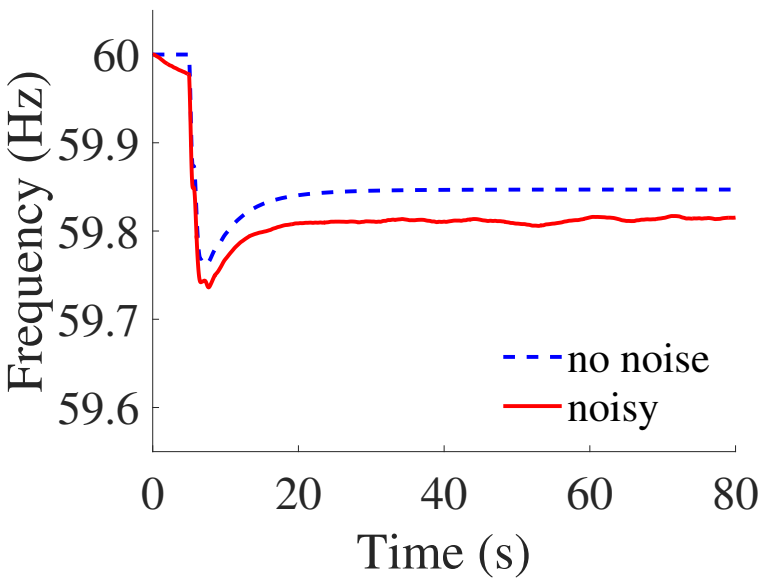
Patch: **leaky** decentralized integral control

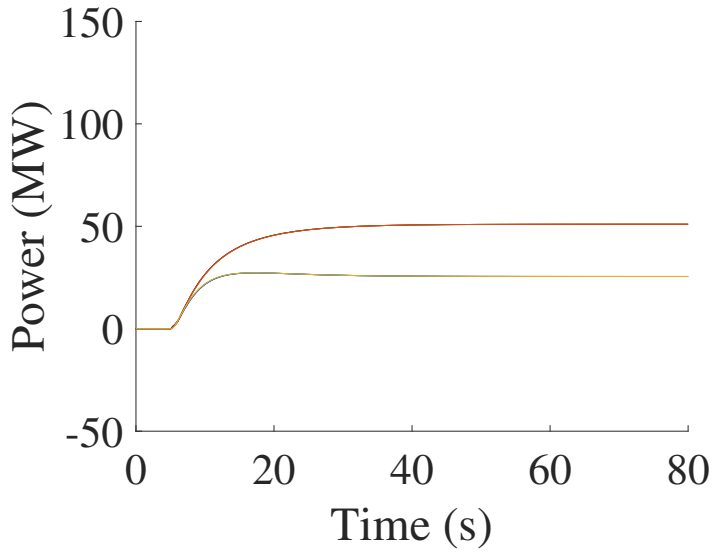
→ **leaky** decentralized integral control

$$\tau_i \dot{\eta}_i = -\Delta\omega_i - \boldsymbol{K\eta}$$

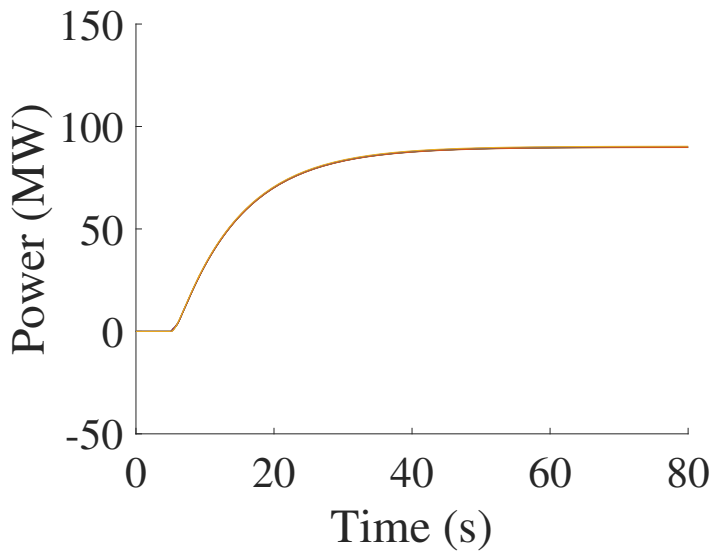
$$u_i = (\nabla J_i)^{-1}(\eta)$$

or lag element or low-pass filter





↑ no noise noise ↓



Leaky integral control can achieve all desired specifications **approximately**

(covered on the board)

Details & initial condition for further reading

Robust Decentralized Secondary Frequency Control in Power Systems: Merits and Tradeoffs

Erik Weitenberg, Yan Jiang, Changhong Zhao, *Member, IEEE*, Enrique Mallada, *Member, IEEE*, Claudio De Persis, and Florian Dörfler

***Abstract*—Frequency restoration in power systems is conventionally performed by broadcasting a centralized signal to local controllers. As a result of energy transition, technological advances, and scientific interest in distributed control and optimization methods, a plethora of distributed frequency control strategies have been proposed recently, which rely on communication amongst local controllers. In this paper, we propose a fully decentralized leaky integral controller for frequency restoration, which is derived from a classic lag element. We study steady-state, asymptotic optimality, nominal stability, input-to-state stability, noise rejection, transient performance, and robustness properties of this controller in closed loop with a nonlinear and multivariable power system model. We demonstrate that the leaky integral controller can strike an acceptable tradeoff between performance and robustness as well as between asymptotic disturbance rejection and transient convergence rate by tuning its dc gain and time constant. We compare our findings to conventional decentralized integral control and distributed-averaging-based integral control in theory and simulations.**

I. Introduction

THE core operation principle of an ac power system is to balance supply and demand in approximately real time. Any instantaneous imbalance results in a deviation of global system frequency from its nominal value. Thus, a central control task is to regulate the frequency in an economically efficient way and despite fluctuating loads, variable generation, and possibly faults. Frequency control is conventionally performed in a hierarchical architecture: The foundation is made of the generators' rotational inertia providing an instantaneous frequency response, and three control layers—primary (droop), secondary automatic generation (AGC), and tertiary (economic dispatch)—operate at different time scales on top of it [1], [2]. Conventionally, droop controllers are installed at synchronous machines and operate fully decentralized, but they cannot by themselves restore the system frequency to its nominal value. To ensure a correct steady-state frequency and a fair power sharing among generators, centralized AGC and economic dispatch schemes are employed on longer time scales.