

Network Aspects of Low-Inertia Systems

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EECI School M19, June 20-23, 2022, Stockholm

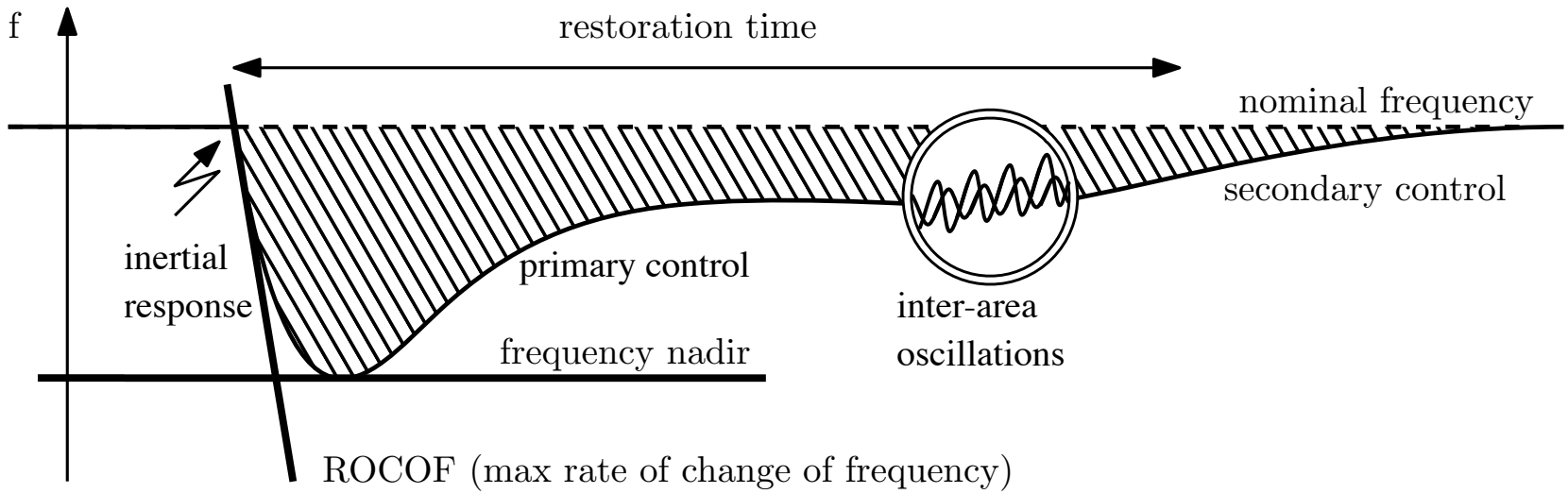
Outline

- Motivation: low-inertia systems are not(?) all about inertia
- Preliminary insights on aggregated system level
- System-level performance metrics
- Optimal allocation & tuning of virtual inertia
- Ancillary services provided by dynamic virtual power plants

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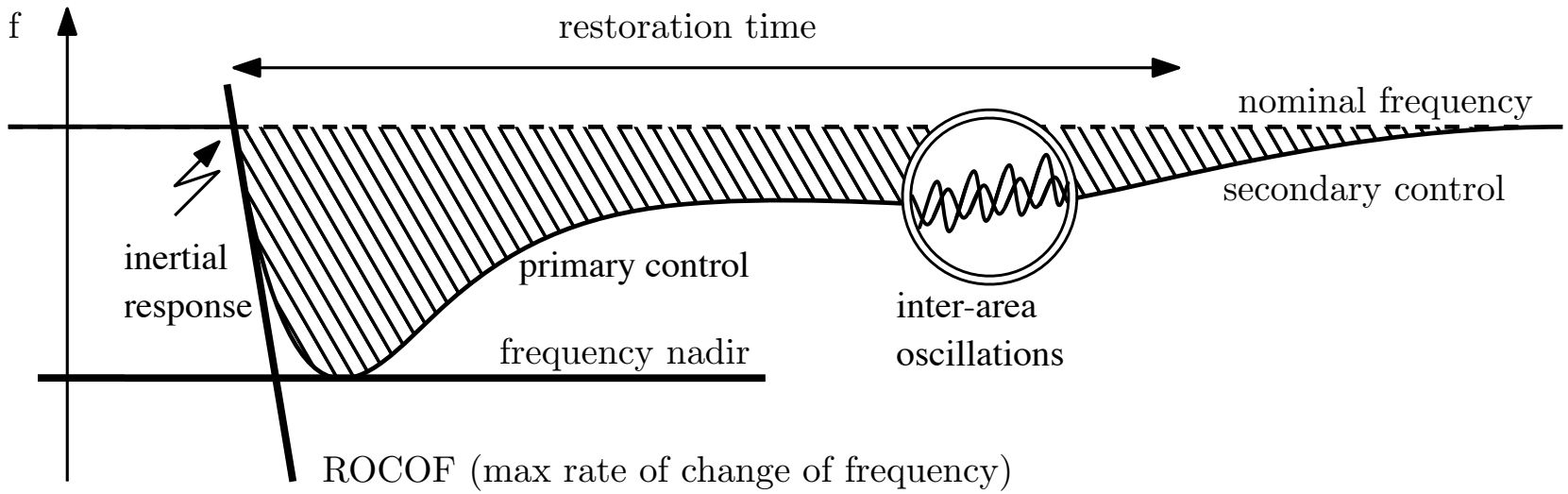
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Recall: fault response & control actions



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

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$\rightarrow$ another perspective on the swing equation

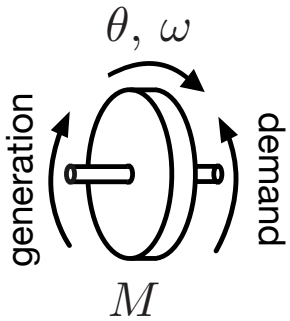
$$(M + M_{\text{virtual}})\,\dot{\omega} + K_{\text{primary}}(\omega - \omega_{\text{ref}}) + K_{\text{secondary}} \int_0^t (\omega - \omega_{\text{ref}})\,d\tau = p(\theta) - p_{\text{ref}}$$

Recall: low inertia & frequency stability

We loose our giant electromechanical low-pass filter:

$$\boldsymbol{M}\,\frac{d}{dt}\,\omega(t) \;=\; P_{\text{generation}}(t) - P_{\text{demand}}(t)$$

change of kinetic energy = instantaneous power balance

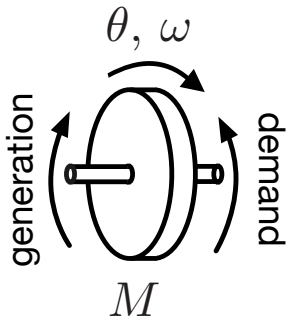


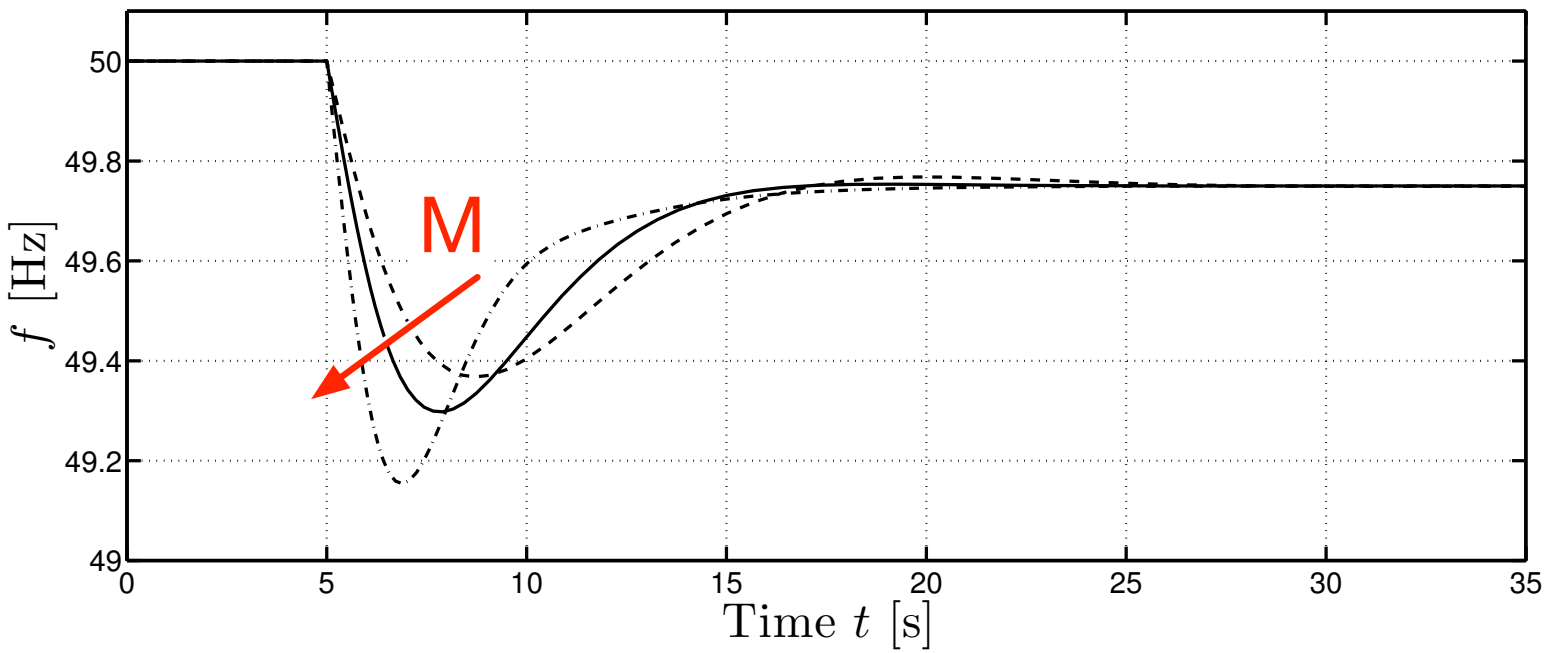
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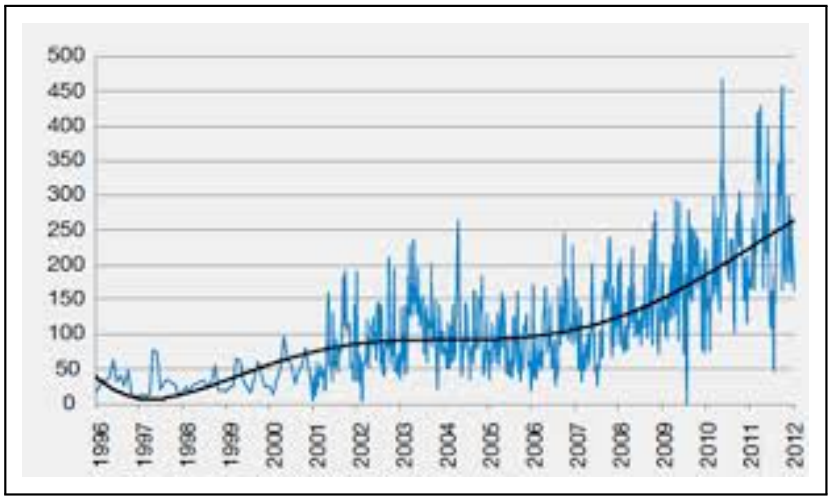
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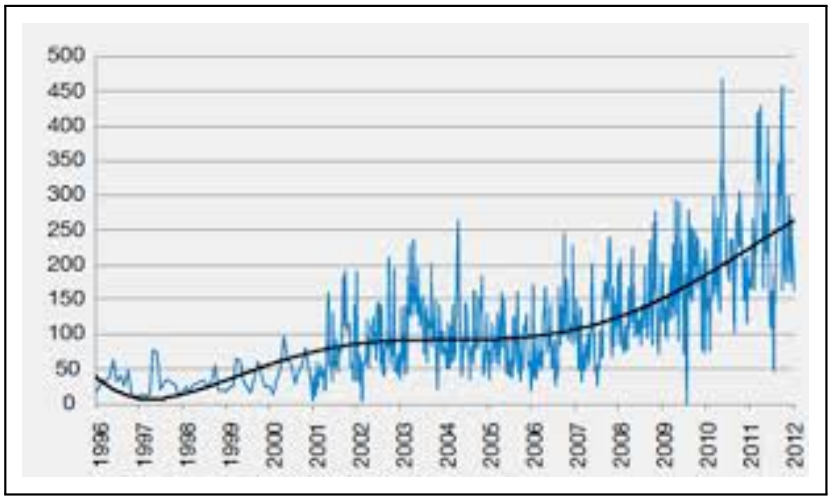


Low-inertia issues close to home

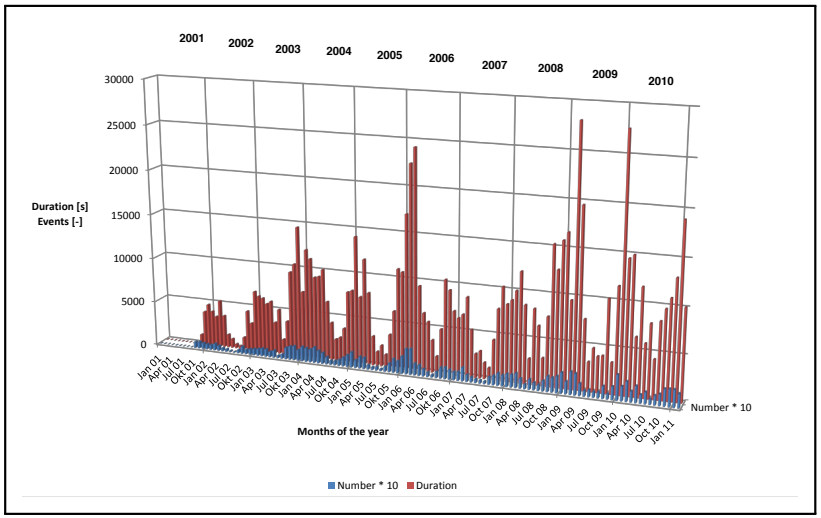


frequency violations in Nordic grid
(source: ENTSO-E)

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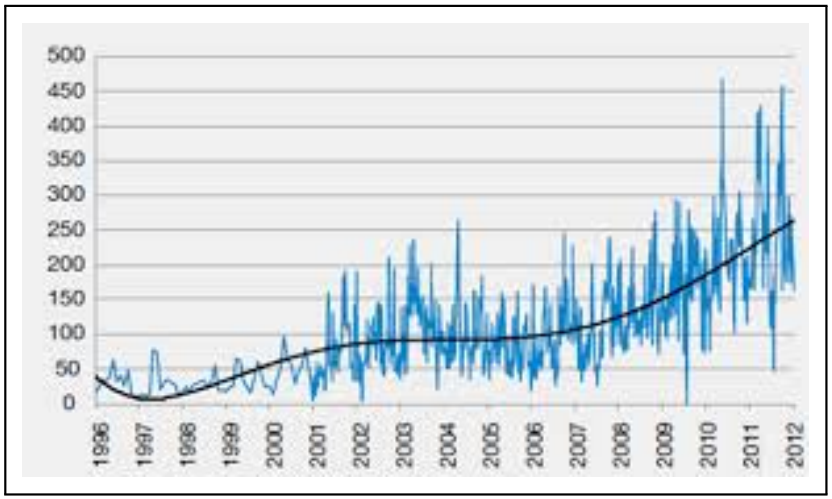


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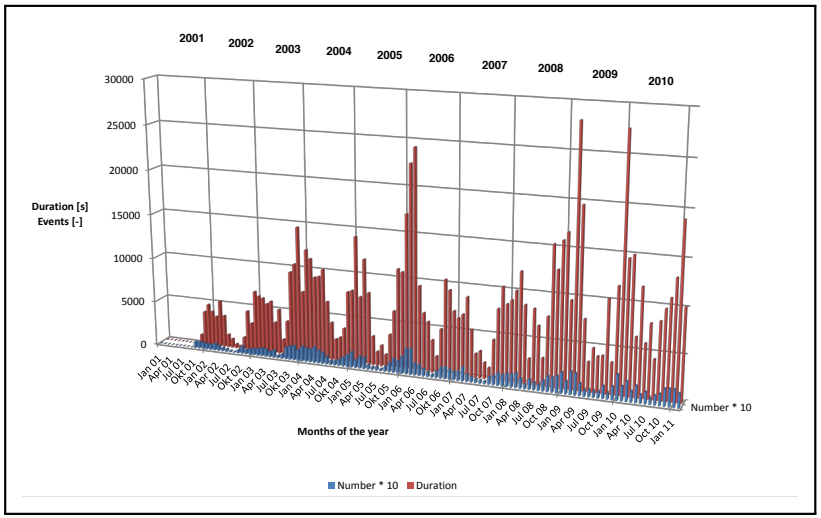


same in Switzerland (source: Swissgrid)

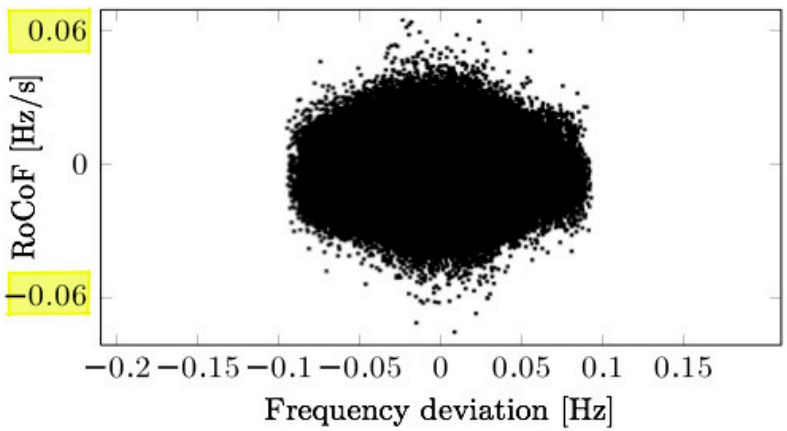
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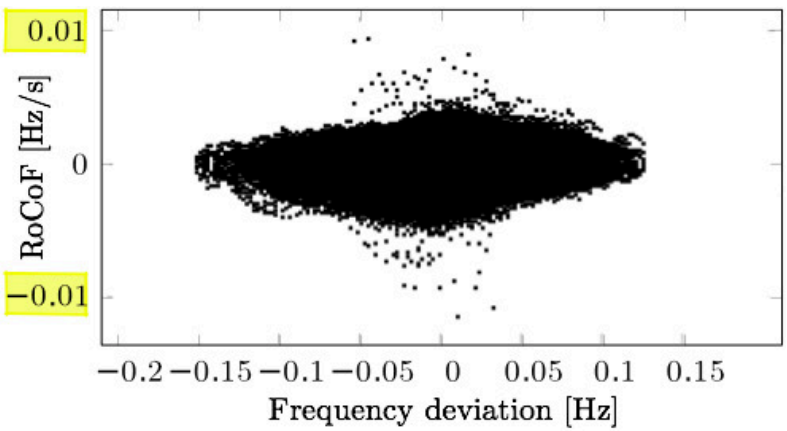
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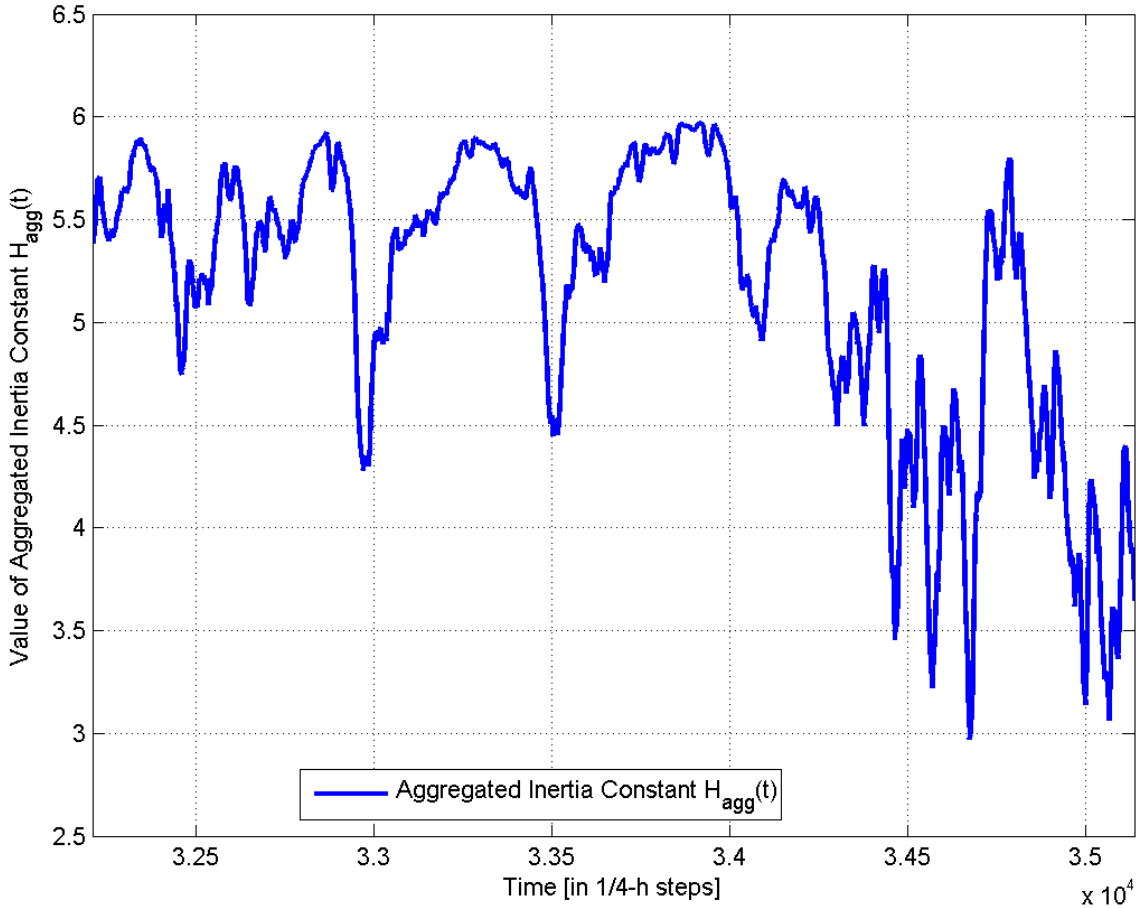
a day in Ireland (source: F. Emiliano)



a year in France (source: RTE)

Time-varying inertia depends on dispatch

"Impact of low rotational inertia on power system stability and operation" by Ulbig et al.



Temporal variation of the aggregated & normalized inertia constant $H = \frac{\frac{1}{2} J\omega^2}{2 \cdot \text{base} \cdot \omega_{\text{ref}}}$ across Germany for the last quarter of 2013

Fast frequency response (or virtual inertia) is becoming a technology & a product

so let's see how we can make use of it

IRELAND

Hybrid storage system looks to Ireland's services market

22 November 2016 by Sara Verbruggen , Be the first to comment

IRELAND: The pilot of a 576kW grid storage system using flywheels and batteries by Dublin-based Schwungrad Energie is loc... technology's deployment in Ireland's ancil...



Flywheel technology was provided by US firm Beacon Power

Schwungrad Energie intends to develop a comm... storage plant for Ireland's DS3 System Services ... a 20MW/10MWh flywheel and lead-acid battery ... provide 5-20 minutes of power at full output.

Pure-play battery or hybrid grid energy storage?

Oct 11, 2016 12:54 PM BST | 0 | Share



...tracapacitor Energy Storage System. System Integrator: Win ...echnologies.

Can Synthetic Inertia from Wind Power Stabilize Grids?

By Peter Fairley
Posted 7 Nov 2016 | 21:00 GMT



Photo: iStockphoto

Quebec's wind farms can produce bursts of power to stabilize AC grid frequency

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Swing equation analysis

(covered on the board)

things become more interesting
when including source dynamics

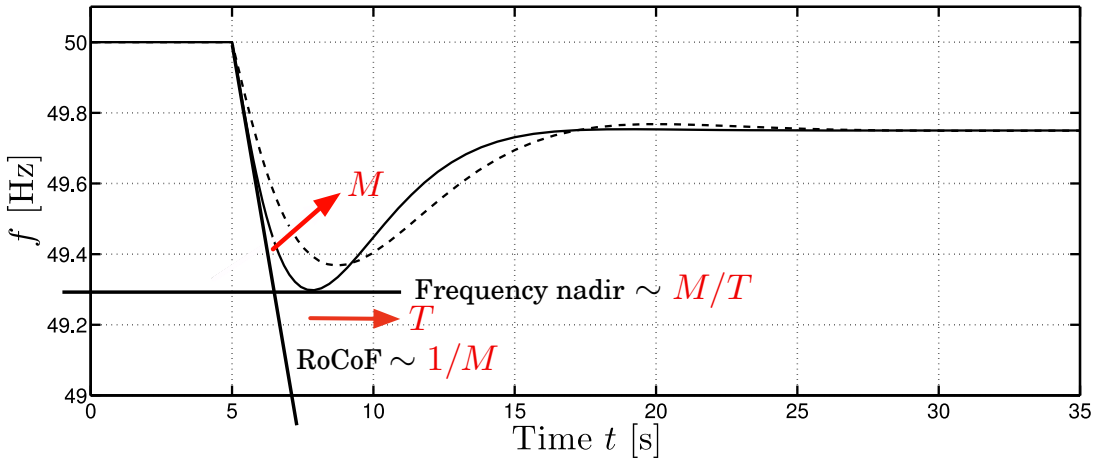
The role of inertia & source time constants

applies to synchronous machines & voltage source converters

aggregated model with source, e.g., turbine or battery

$$M \tfrac{d}{dt}\omega = p - p_d$$

$$T \tfrac{d}{dt}p = -p + K\omega$$



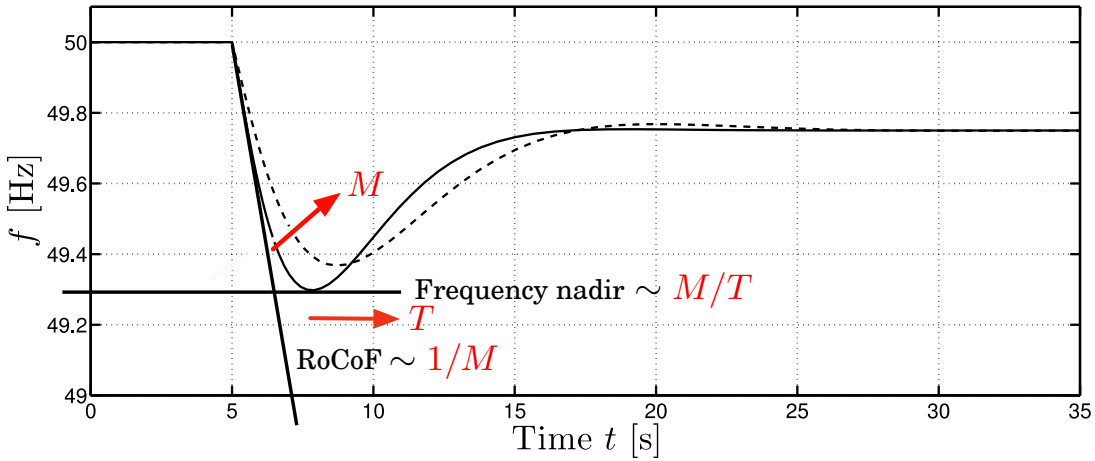
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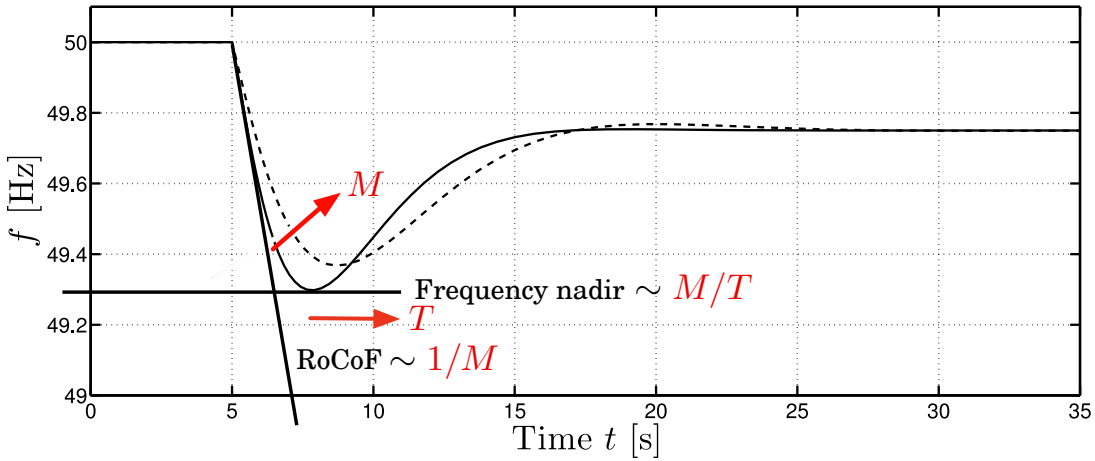
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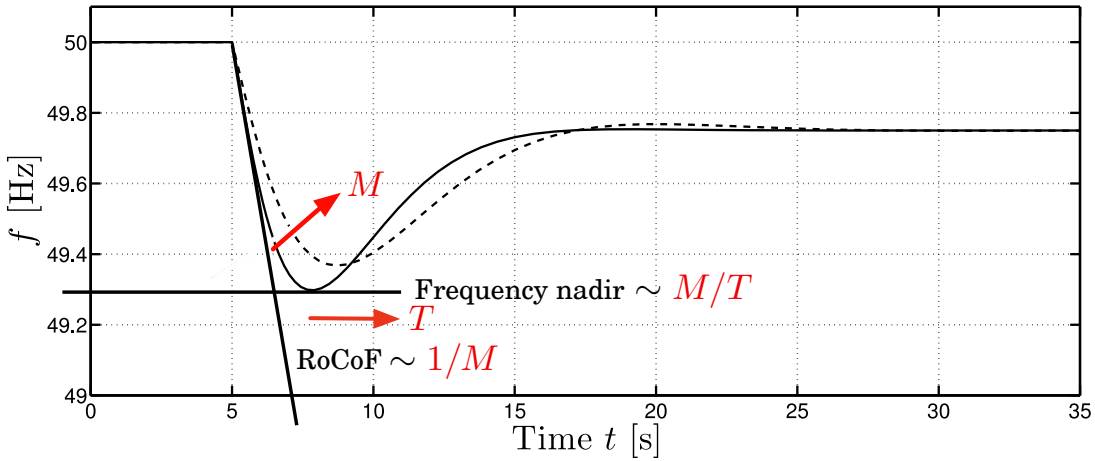
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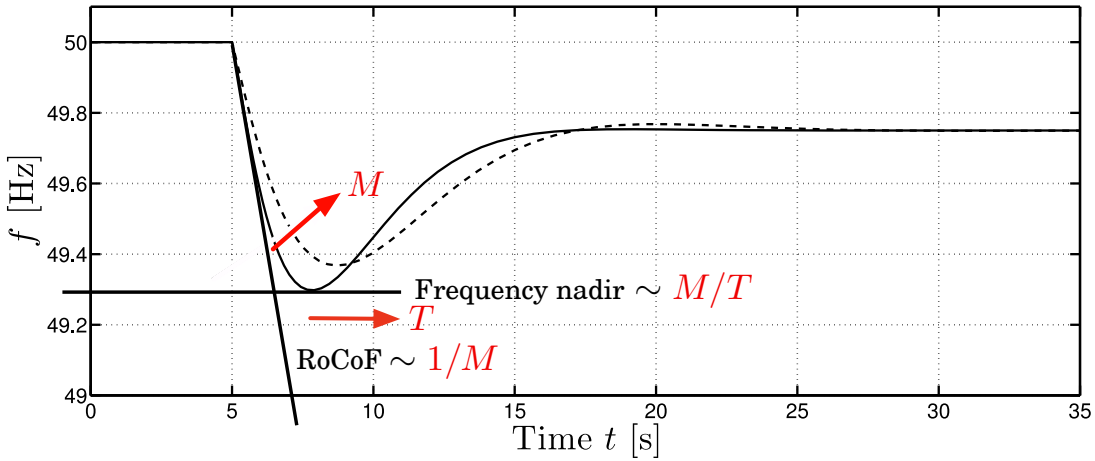
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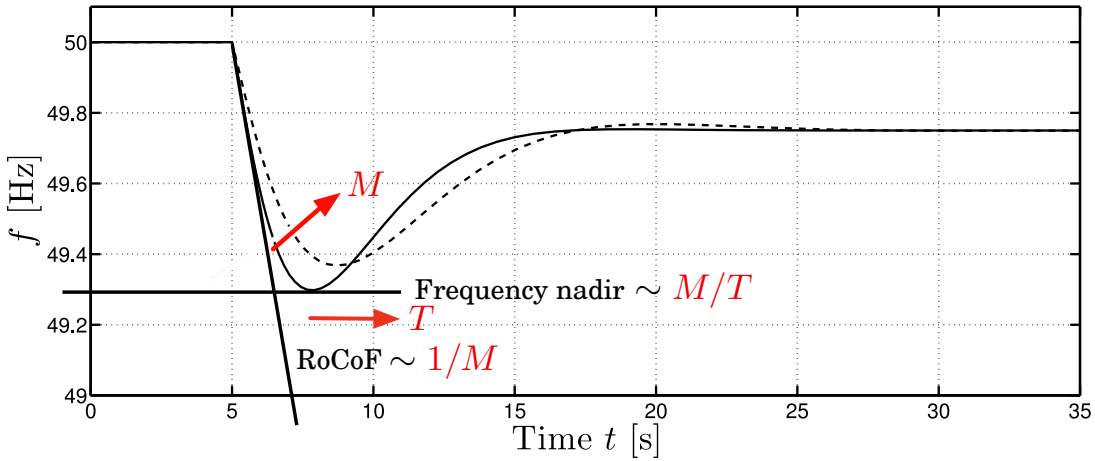
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  $\longrightarrow$ RoCoF not indicative of fault in low-inertia system $\rightarrow$ questionable

case study suggest that we do not need a lot of inertia as long as we have fast source dynamics for regulation . . .

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control perspective on

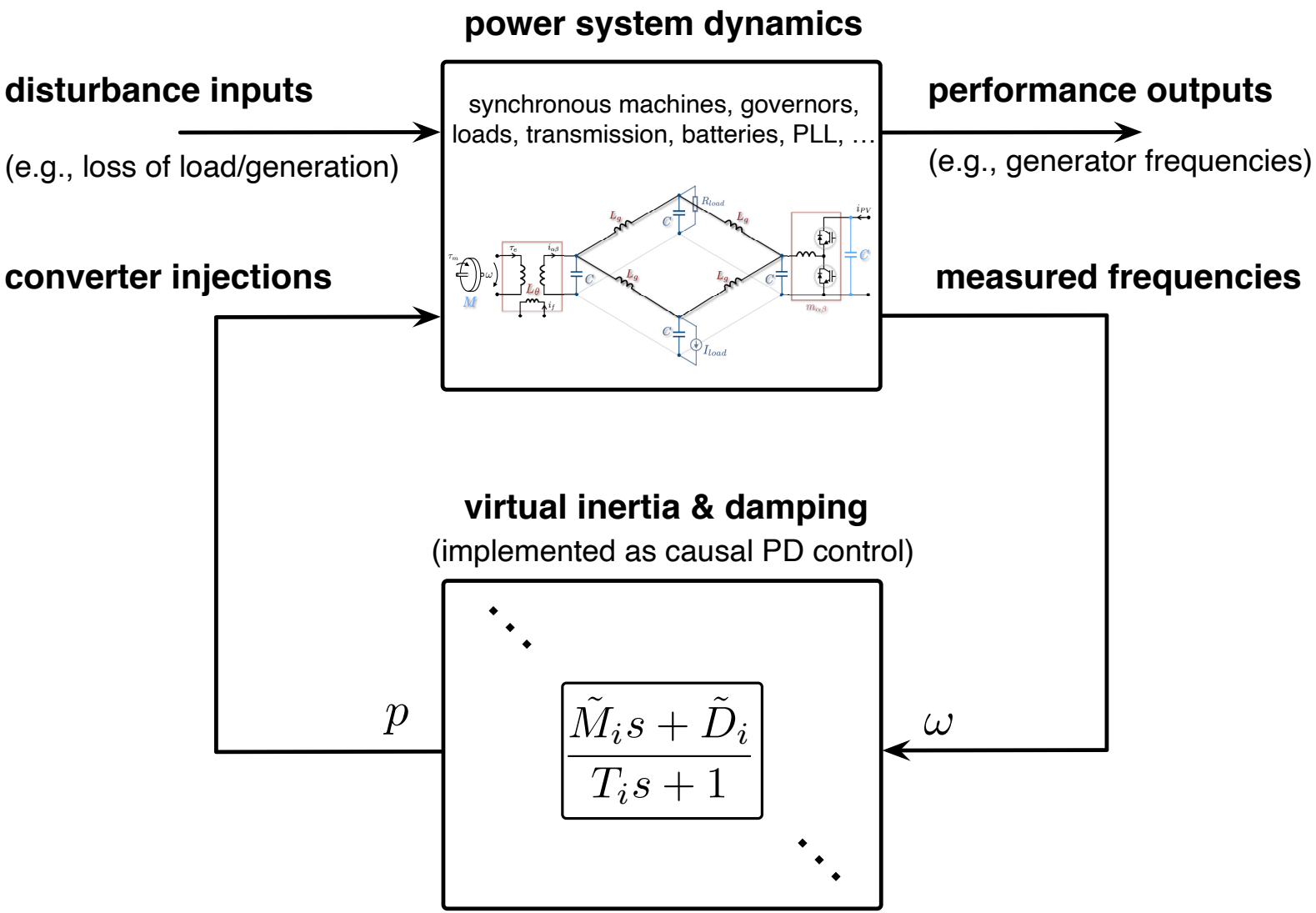
fast-frequency response

colloquially

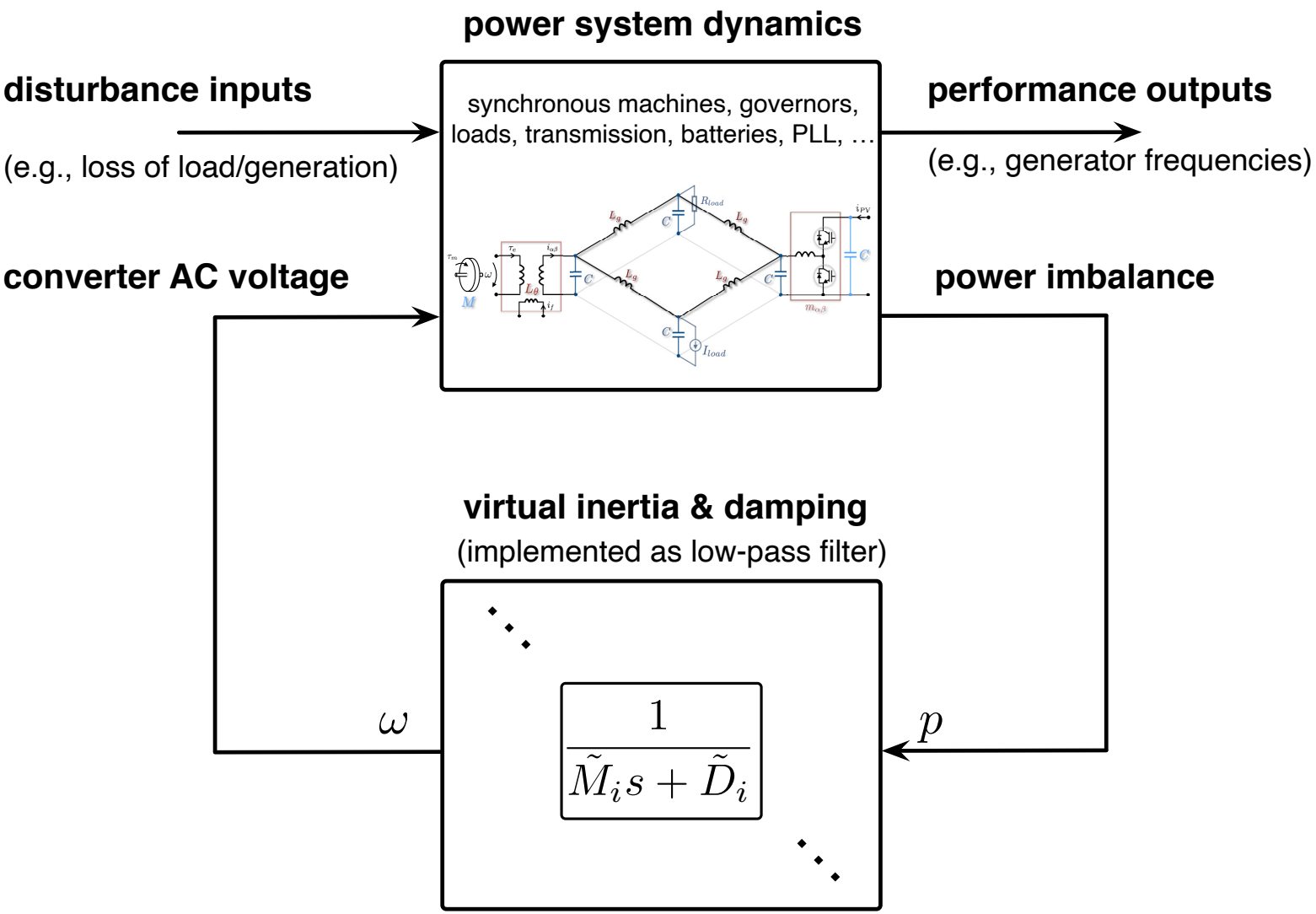
$\approx$

virtual inertia / damping

Power system in **feedback** with **grid-following** fast-frequency control



Power system in **feedback** with **grid-forming** fast-frequency control



Filtered droop $\rightarrow$ virtual inertia & damping

(covered on the board)

these are parametric controllers which we can tune by means of optimization !

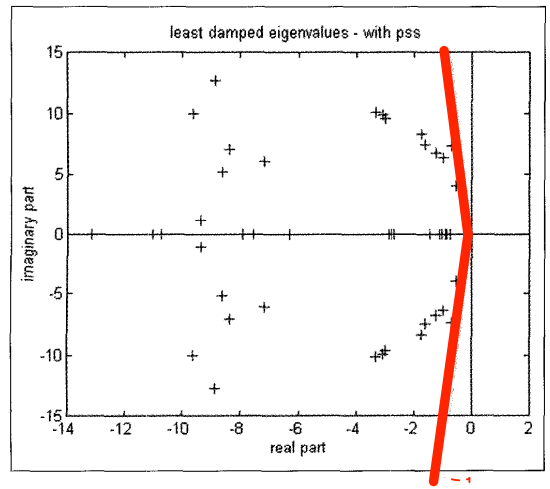
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which metric(s) should we optimize ?

Historic & revived (PMUs) metrics: spectrum, nadir, RoCoF, & total inertia

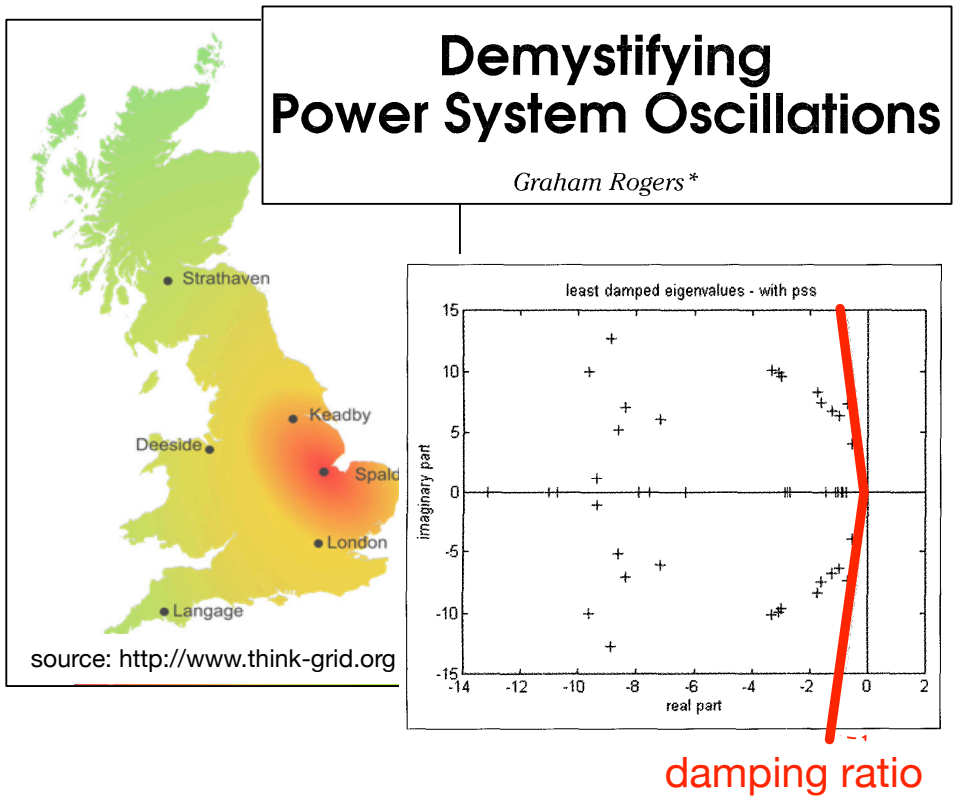
Demystifying Power System Oscillations

*Graham Rogers**



damping ratio

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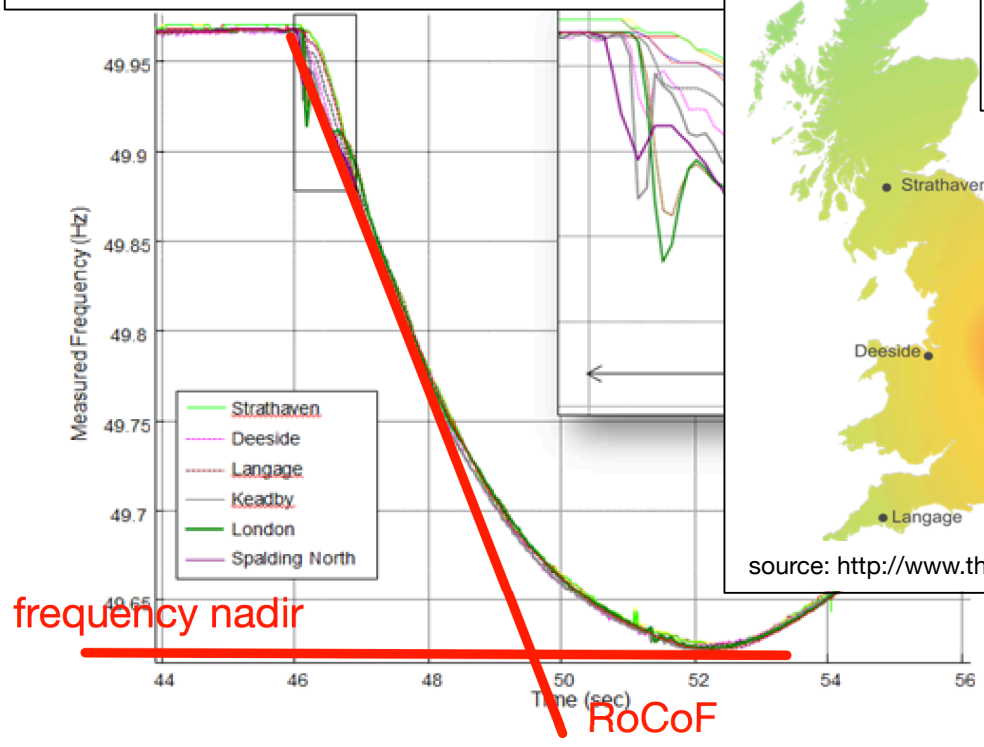
Smart Frequency Control for the Future GB Power System

Peter Wall, Negar Shams, Vladimir Terzija
The University of Manchester
Manchester, UK

Vandad Hamidi, Charlotte Grant
National Grid
Warwick, UK

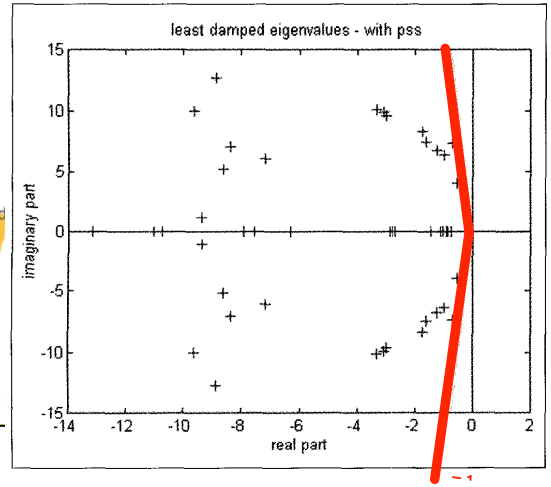
Douglas Wilson, Seán Norris, Kyriaki Maleka
Alstom Grid
Edinburgh, UK

Campbell Booth, Qiteng Hong, Andrew Roscoe



Demystifying Power System Oscillations

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Smart Frequency Contro[illegible]
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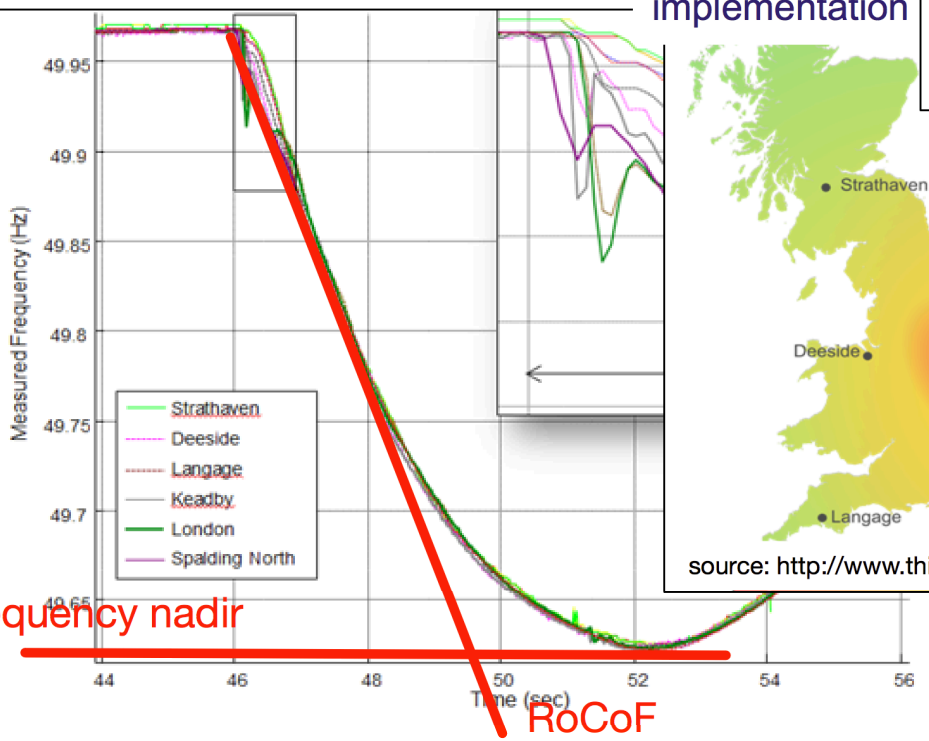
European Network of Transmission System Operators for Electricity — entsoe

Need for synthetic inertia (SI) for frequency regulation

ENTSO-E guida[illegible]
implementation

Demystifying Power System Oscillations

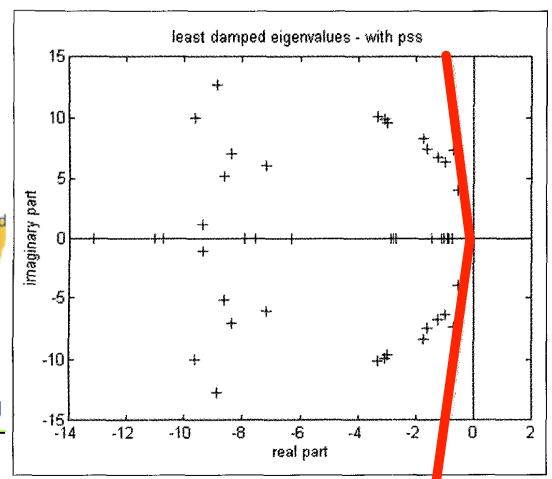
*Graham Rogers**



frequency nadir

RoCoF

source: http://www.think-grid.org

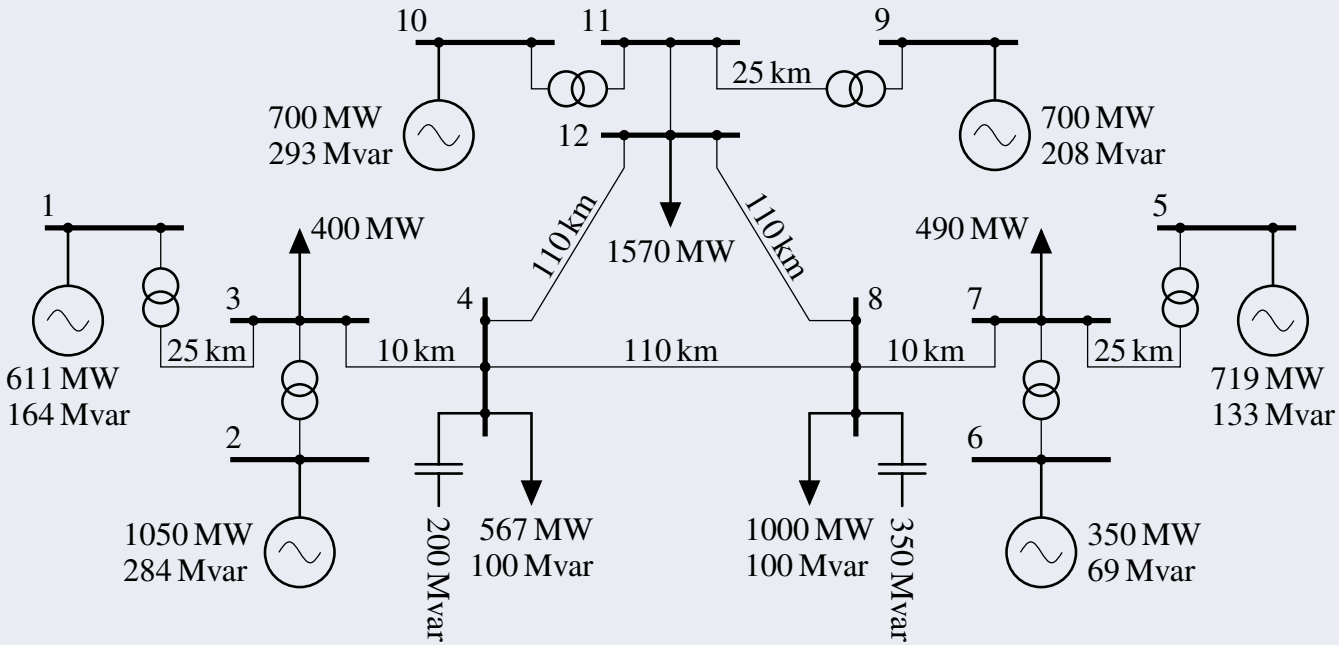


damping ratio

are these suitable metrics ?

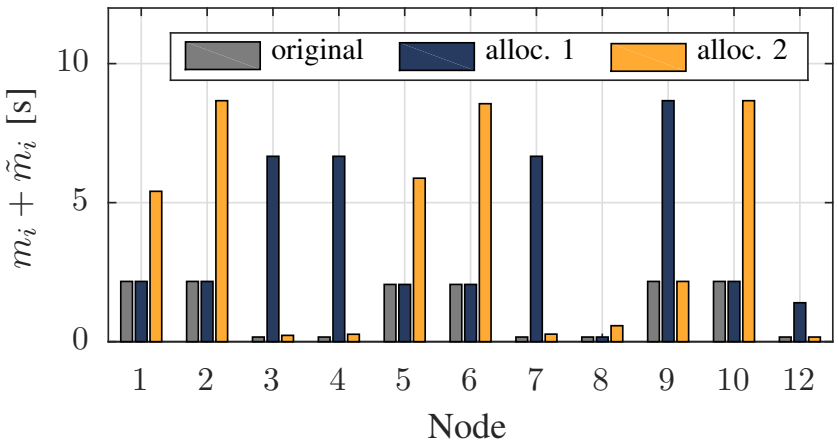
let’s look at a case study

Modified Kundur three-area case study



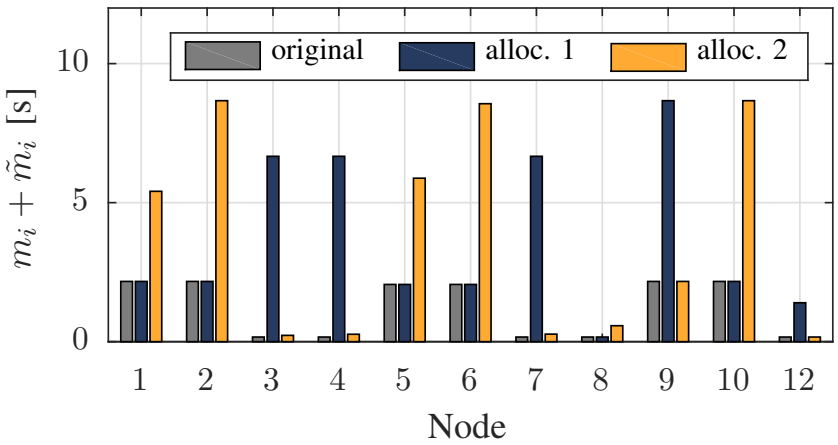
- added third area to standard case
- PLLs at all buses for inertia emulation (overall device response time $\sim$100ms)
- transformer reactance 0.15 p.u, line impedance (0.0001+0.001i) p.u./km
- original inertia 40s: removed 28s of rotational which can be re-allocated as virtual inertia
- added governors & droop control at all generators

RoCoF, spectrum, & inertia $\rightarrow$ poor metrics

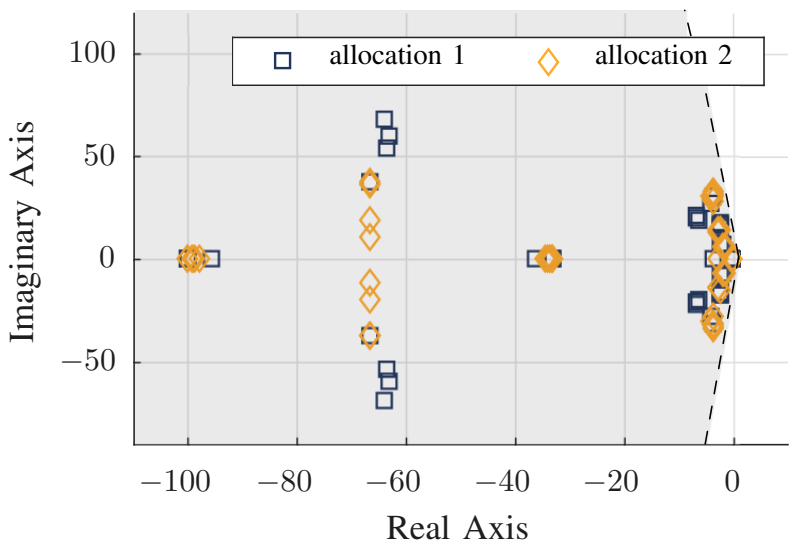


metrics	allocation 1	allocation 2
total inertia	40.85 s	40.85 s

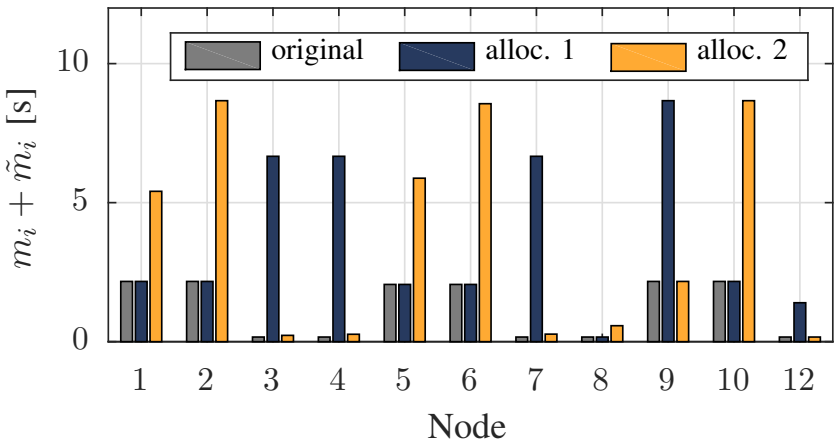
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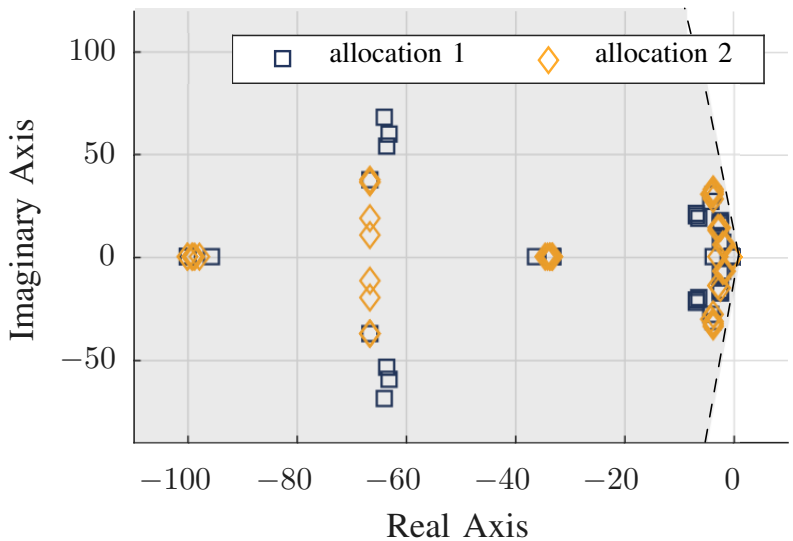
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total inertia	40.85 s	40.85 s
damping ratio	0.1190	0.1206



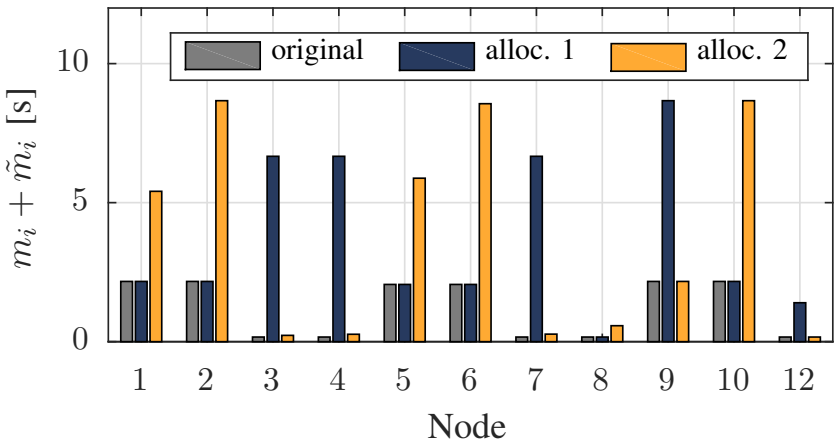
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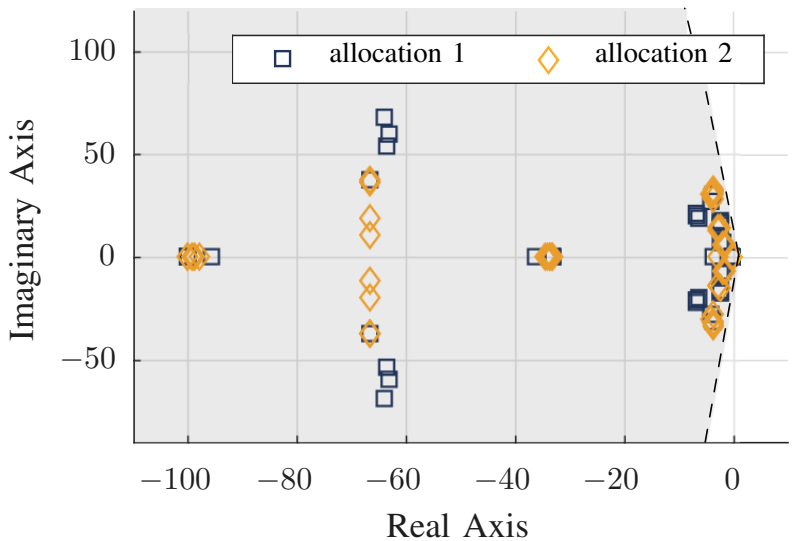
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RoCoF	0.8149 Hz/s	0.8135 Hz/s



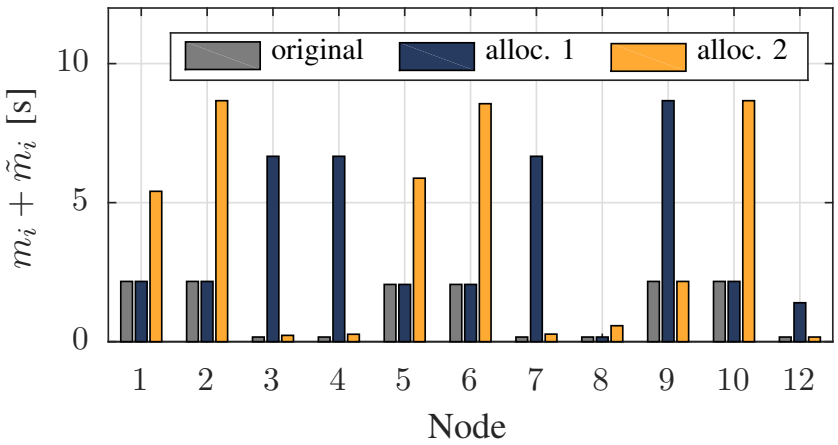
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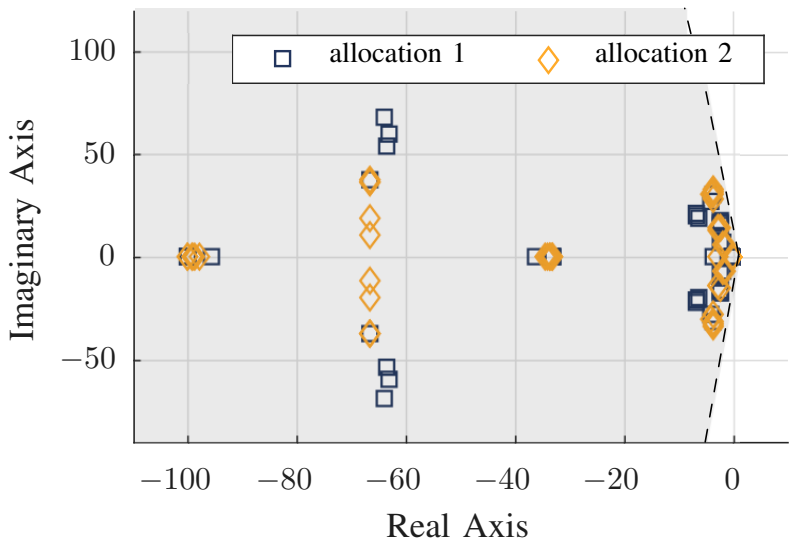
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ω nadir	-84.8 mHz	-65.1 mHz
peak injection	118.38 MW	7.0446 MW
control effort	15.581	2.699



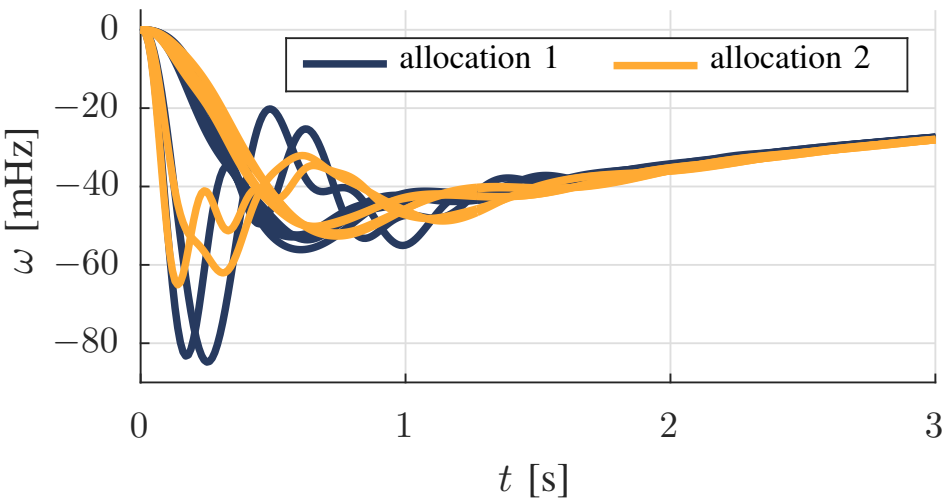
RoCoF, spectrum, & inertia → poor metrics



metrics	allocation 1	allocation 2
total inertia	40.85 s	40.85 s
damping ratio	0.1190	0.1206
RoCoF	0.8149 Hz/s	0.8135 Hz/s
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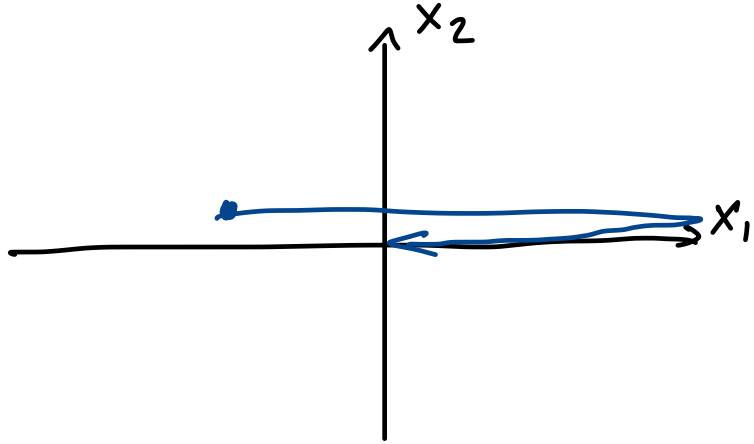


comparison for 100 MW load step at bus 7



Analytic insights on board

(covered on the board)



Example: $\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} -1 & 10^5 \\ 0 & -\sqrt{3} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$

Eigenvalues are $\{-1, -\sqrt{3}\}$

$$x_2(t) = x_2(0)\, e^{-\sqrt{3}t}$$

$$x_1(t) = x_1(0)\, e^{-t} + 10^5 \int_0^t e^{t-\tau}\, x_2(\tau)\, d\tau$$

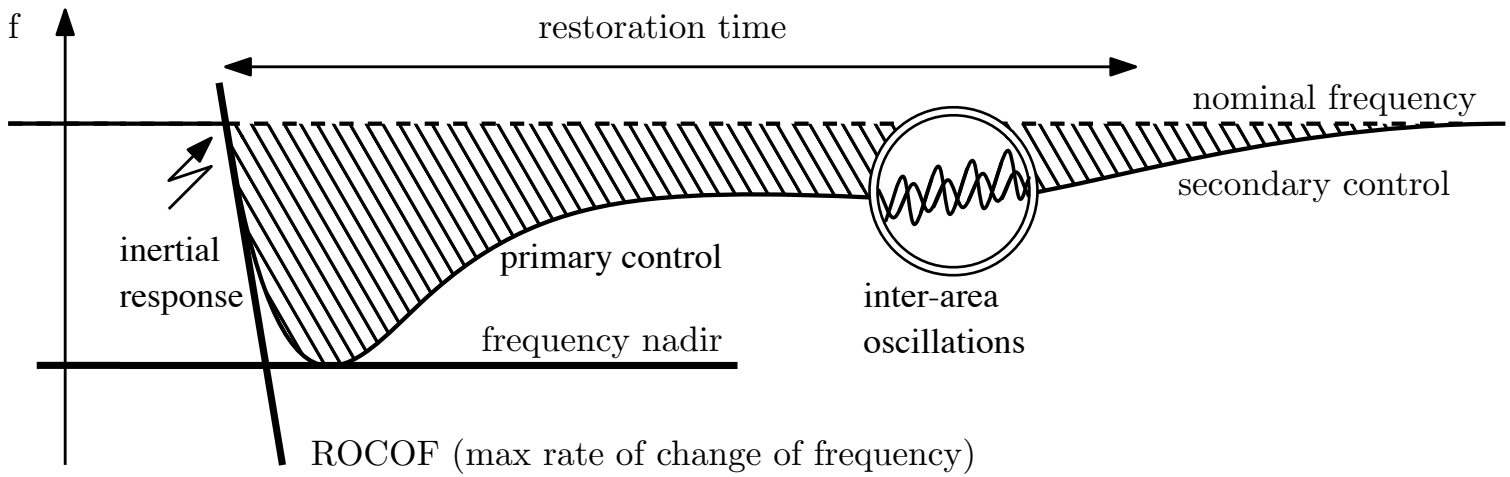
eigenvalues are a poor metric for transient behavior or disturbance amplification

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} -1 & 10^5 \\ 0 & -\sqrt{3} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \eta \end{bmatrix}$$

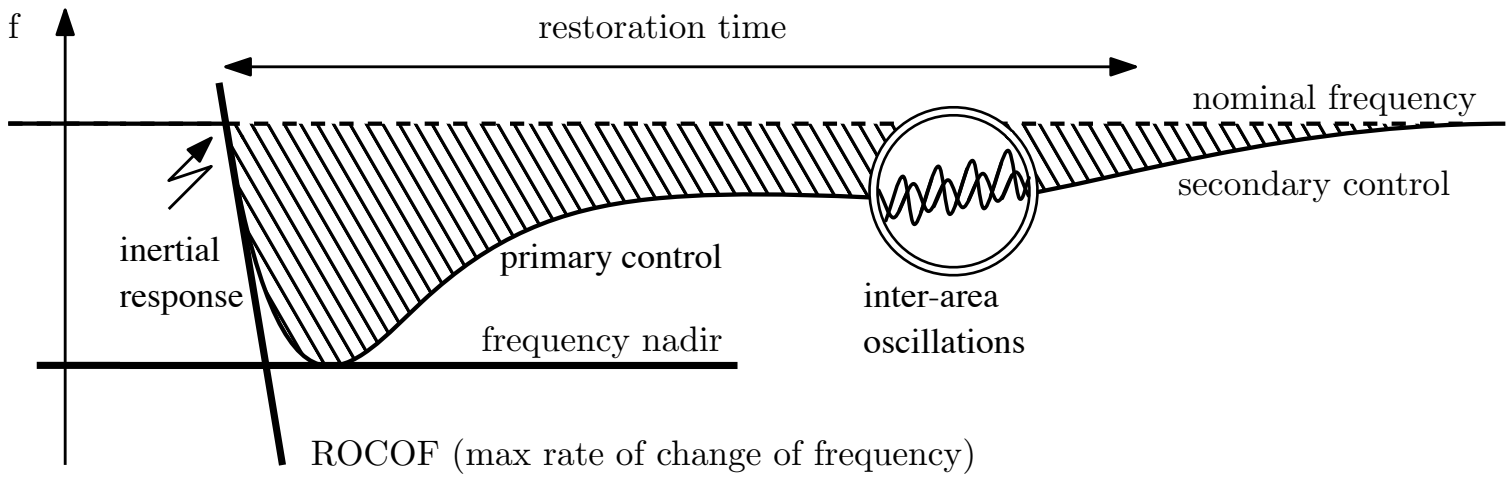
disturbance

η will be amplified by 10^5 before hitting x_1

Performance metrics for power systems



Performance metrics for power systems



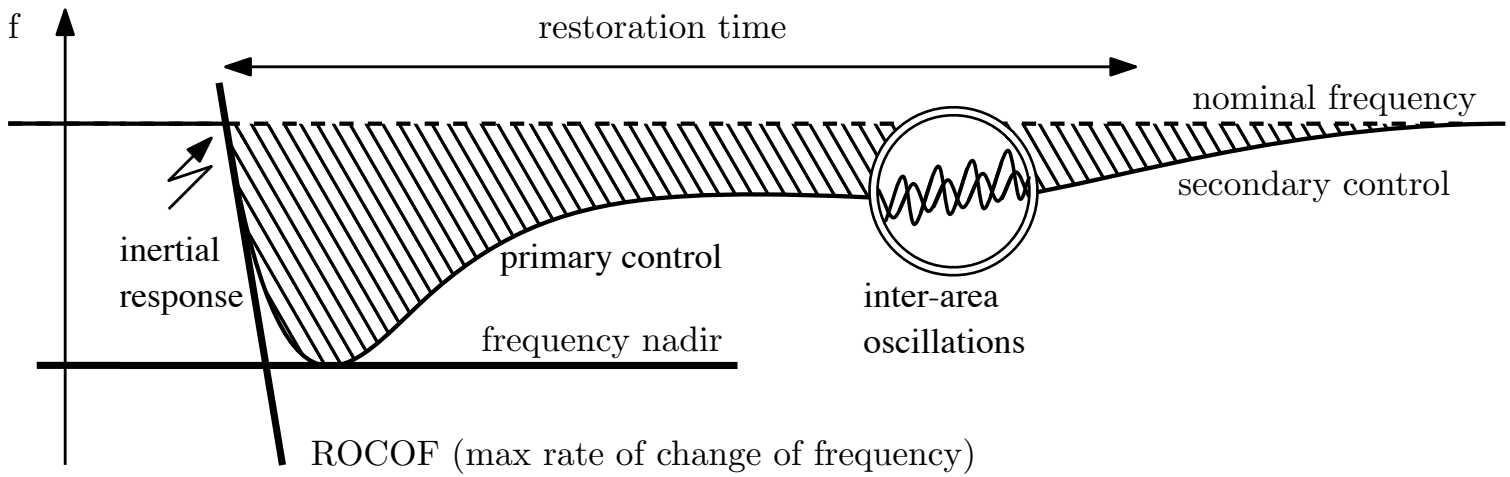
system norm quantifying signal amplifications

disturbances:
impulse (fault), step (loss of unit), white noise (renewables)



performance outputs: integral, peak, RoCoF, restoration time, ...

Performance metrics for power systems



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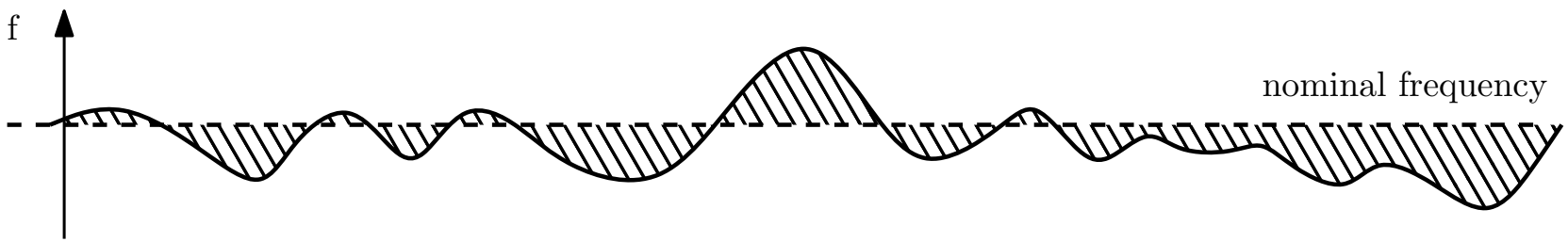
performance outputs: integral, peak, RoCoF, restoration time, ...

Trade-offs: inout/output combination & worst-case vs. average performance

Integral-quadratic performance metric

recall: the post-fault response in a low-inertia system may look very different

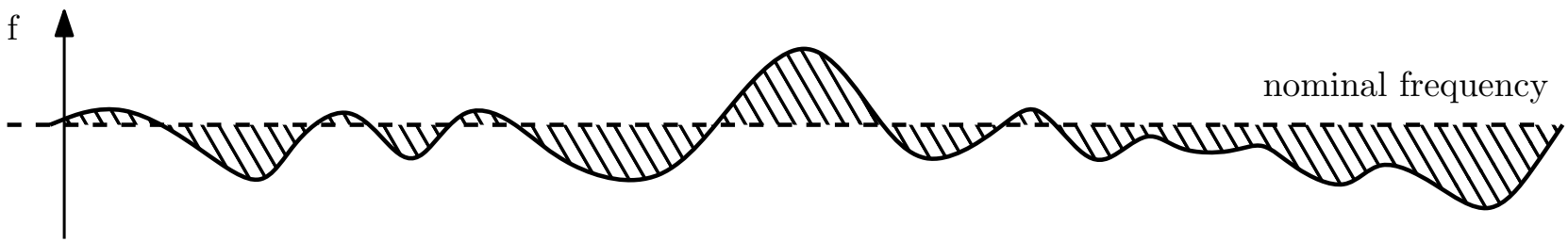
$$\int_0^\infty x(t)^T Q\, x(t)\, dt$$



Integral-quadratic performance metric

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$$\int_0^\infty x(t)^T Q\, x(t)\, dt$$



$\mathcal{H}_2$ **system norm** interpretation: η → system → y

1. **performance output**: $\mathbf{y} = Q^{1/2}x$
2. **impulsive** η (faults) $\longrightarrow$ output energy $\int_0^\infty \mathbf{y}(t)^\mathsf{T}\,\mathbf{y}(t)\, dt$
3. **white noise** η (renewables) $\longrightarrow$ output variance $\lim_{t\to\infty} \mathbb{E}\left(\mathbf{y}(t)^\mathsf{T}\,\mathbf{y}(t)\right)$

Constraints on control inputs

1. **energy constraint**: $\int_0^\infty u^T R\, u\, dt$ directly captured in $\mathcal{H}_2$ framework

Constraints on control inputs

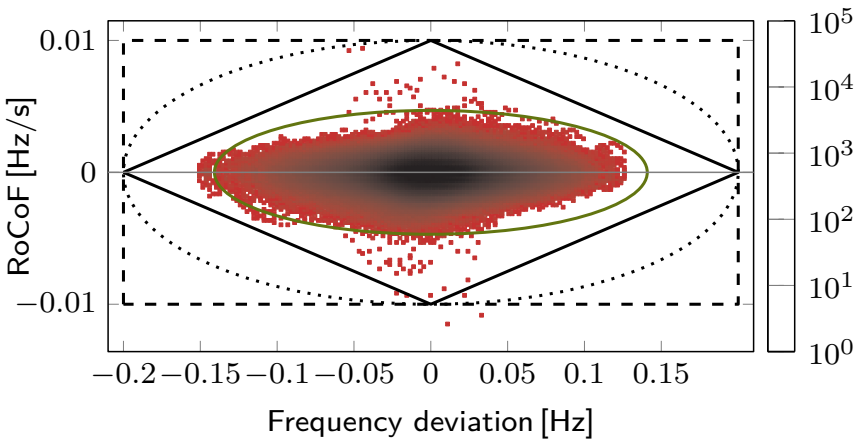
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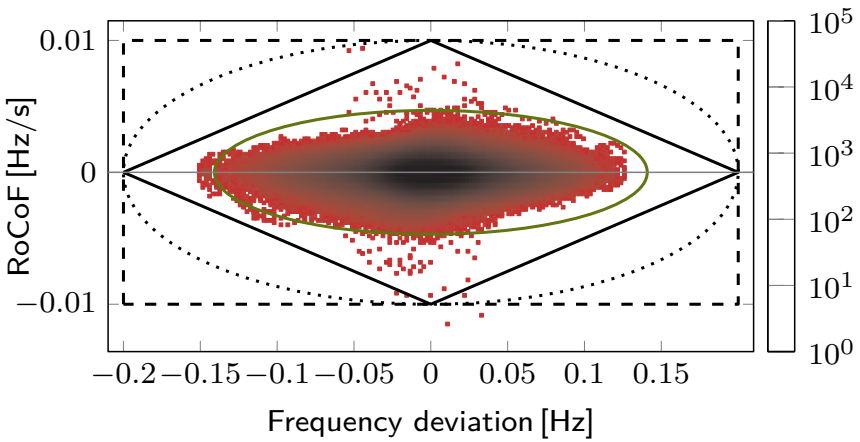


European frequency data (source: RTE)

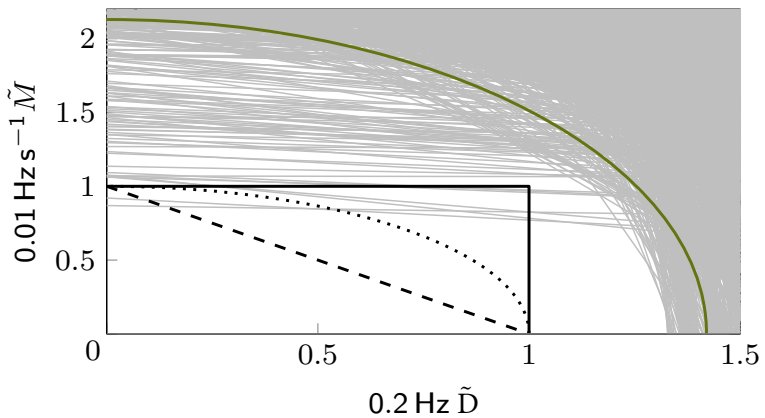
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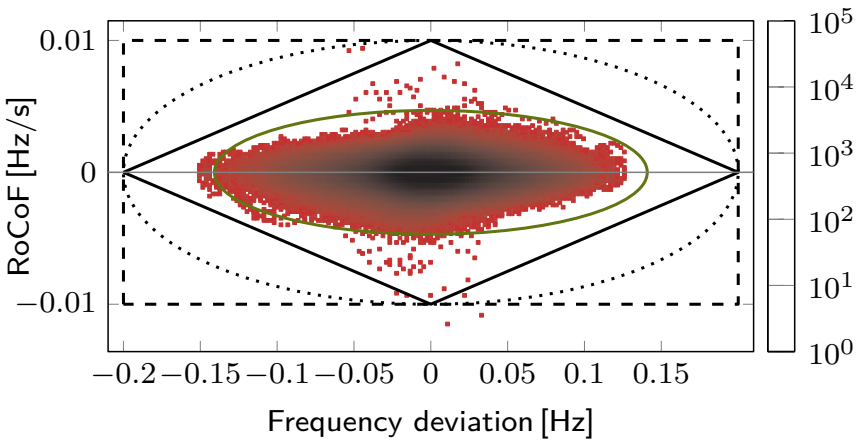
corresponding bounds on gains

$\Rightarrow$ $\|(\omega_i(t), \dot{\omega}_i(t))\|_p$, $\|(\tilde{D}_i, \tilde{M}_i)\|_q$ bounded $(\frac{1}{p} + \frac{1}{q} = 1) \Rightarrow \|u_i(t)\|_{\ell_\infty}$ bounded

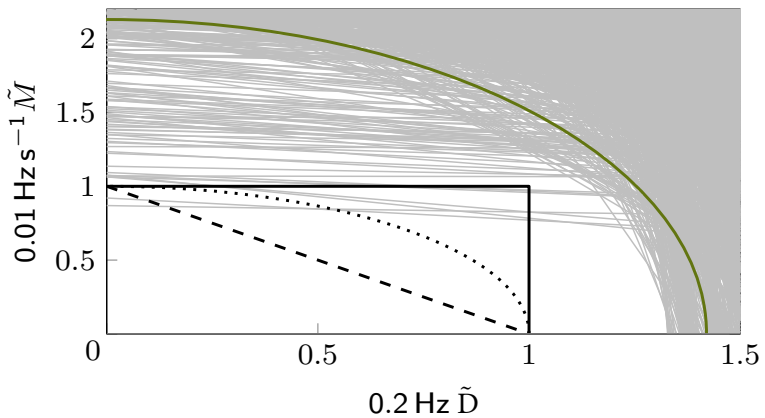
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3. **budget constraint** for finitely many devices: $\sum_i \overline{u_i} = const.$

Derivation of $\mathcal{H}_2$ norm formulae

(covered on the board)

Outline

- Motivation: low-inertia systems are not(?) all about inertia
- Preliminary insights on aggregated system level
- System-level performance metrics
- Optimal allocation & tuning of virtual inertia
- Ancillary services provided by dynamic virtual power plants

(sub)optimize performance
and see what we learn

System model & virtual inertia realization

nonlinear DAE dynamics

$$\dot{x}_s = f_s(x_s, z_s)$$
$$0 = g_s(x_s, z_s, i)$$

x_s : system & control states

z_s : network signals

i : current injections/faults

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virtual inertia & damping

= fast frequency response implemented by means of

- converters & storage
- 2nd-order droop control

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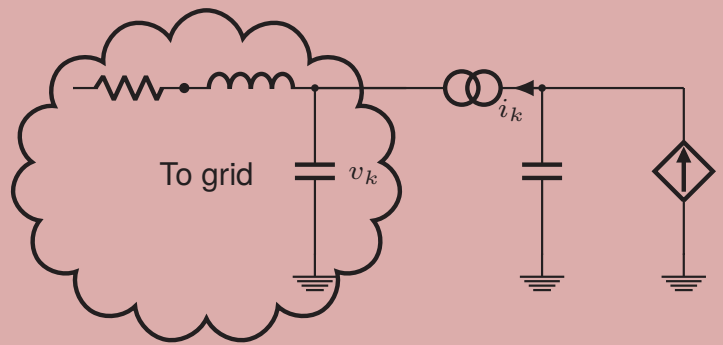
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follow the grid: lock to ω



grid-following

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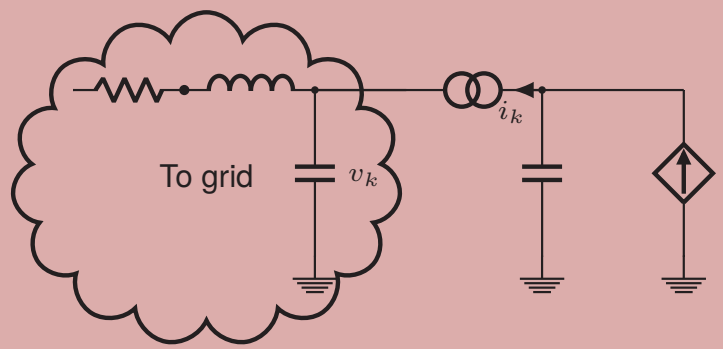
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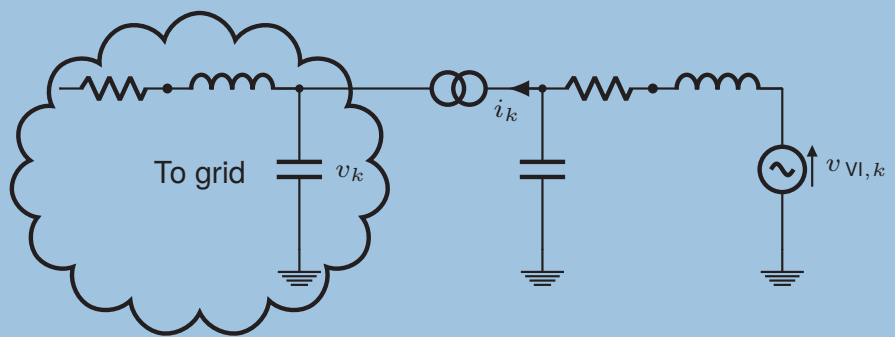
- converters & storage
- 2nd-order droop control

follow the grid: lock to ω



grid-following

form the grid: generate ω

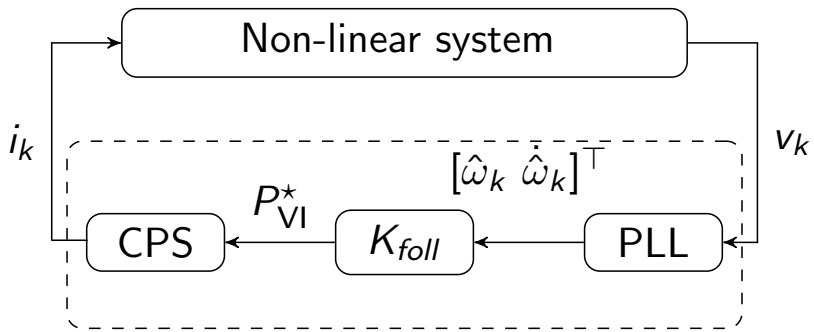


grid-forming

Comparison: virtual inertia implementations

grid-following

$\omega \rightarrow P_{\text{VI}}$



droop via phased-locked loop

$$\dot{\hat{\theta}}_k = \hat{\omega}_k$$

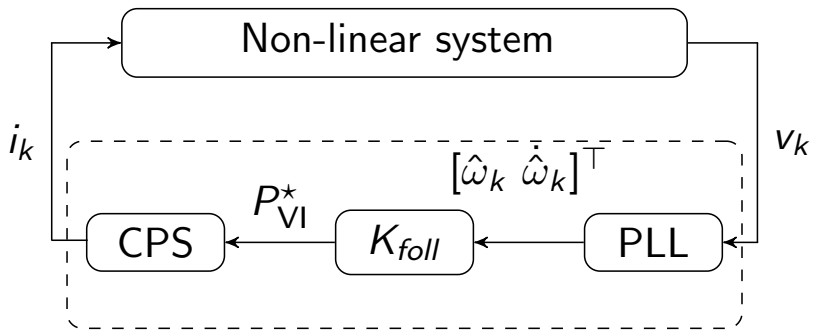
$$\tau_k \dot{\hat{\omega}}_k = -\hat{\omega}_k - K_p v_{q,k} - K_i \int v_{q,k} d\tau$$

$$P^\star_{\text{VI},k} = K_{foll,k} \, [\hat{\omega}_k \ \dot{\hat{\omega}}_k]^\top$$

Comparison: virtual inertia implementations

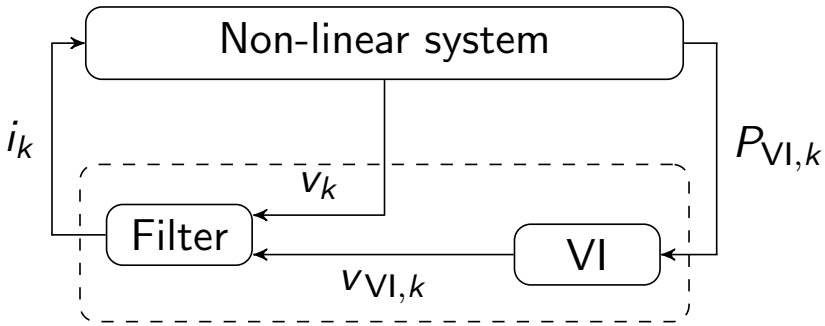
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$P_{\text{VI}} \rightarrow \omega$



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grid-forming 2nd-order droop

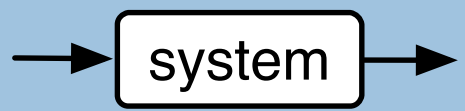
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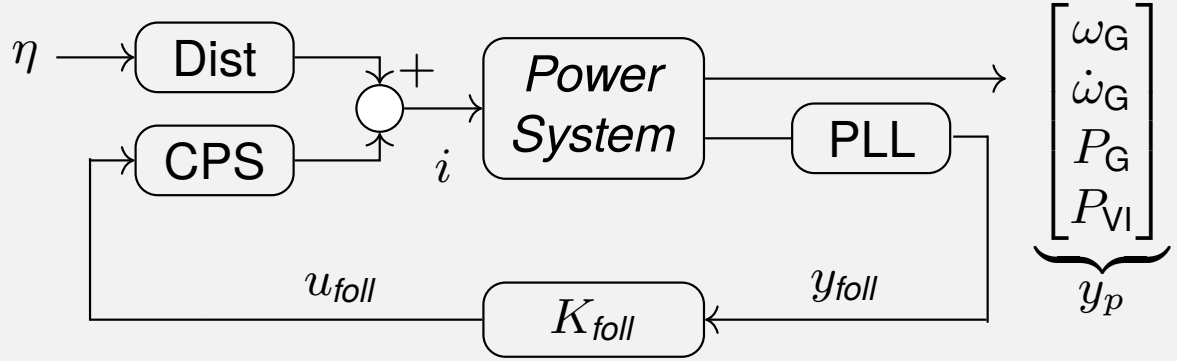
Closed-loop system & linearization

here: grid-following implementation; analogous for grid-forming implementation

disturbances: impulse (fault), step (loss of unit), white noise (renewables)



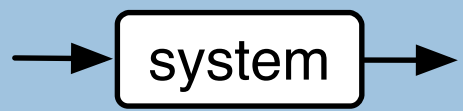
performance outputs: integral, peak, RoCoF, restoration time, . . .



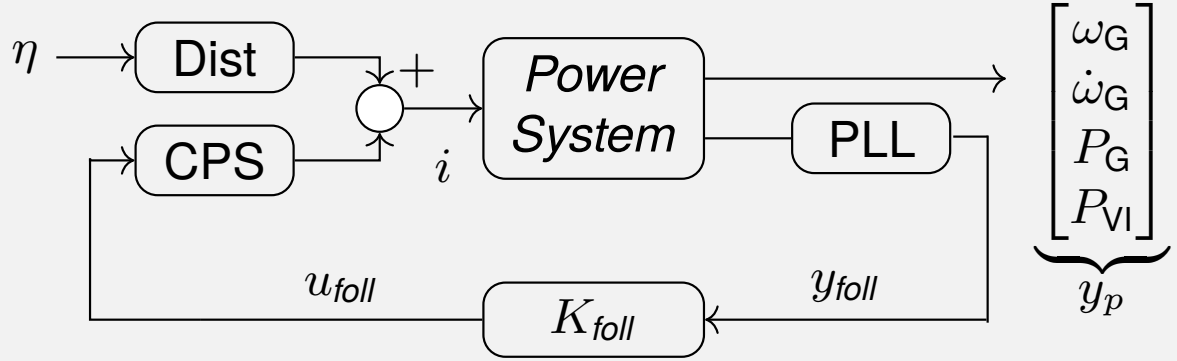
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$$\Delta\dot{x}_{cl} = (A + BKC)\Delta x_{cl} + G\eta, \;\; \Delta y_p = C_p \Delta x_{cl}$$

linearized closed loop for optimal control design

Optimal control formulation

$$
\begin{aligned}
&\underset{P,\,K}{\text{minimize}} && \|G\|_{\mathcal{H}_2}^2 = \text{trace}(G^\top P\, G) && \text{performance metric} \\
&\text{subject to} && K(m,\,d) \in S && \text{constraint set} \\
& && P\,(A + BKC) + (A + BKC)^\top P + G^\top G = \mathbb{O} && \text{Lyapunov equation}
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key insights:

1. **non-convex** problem in P, K

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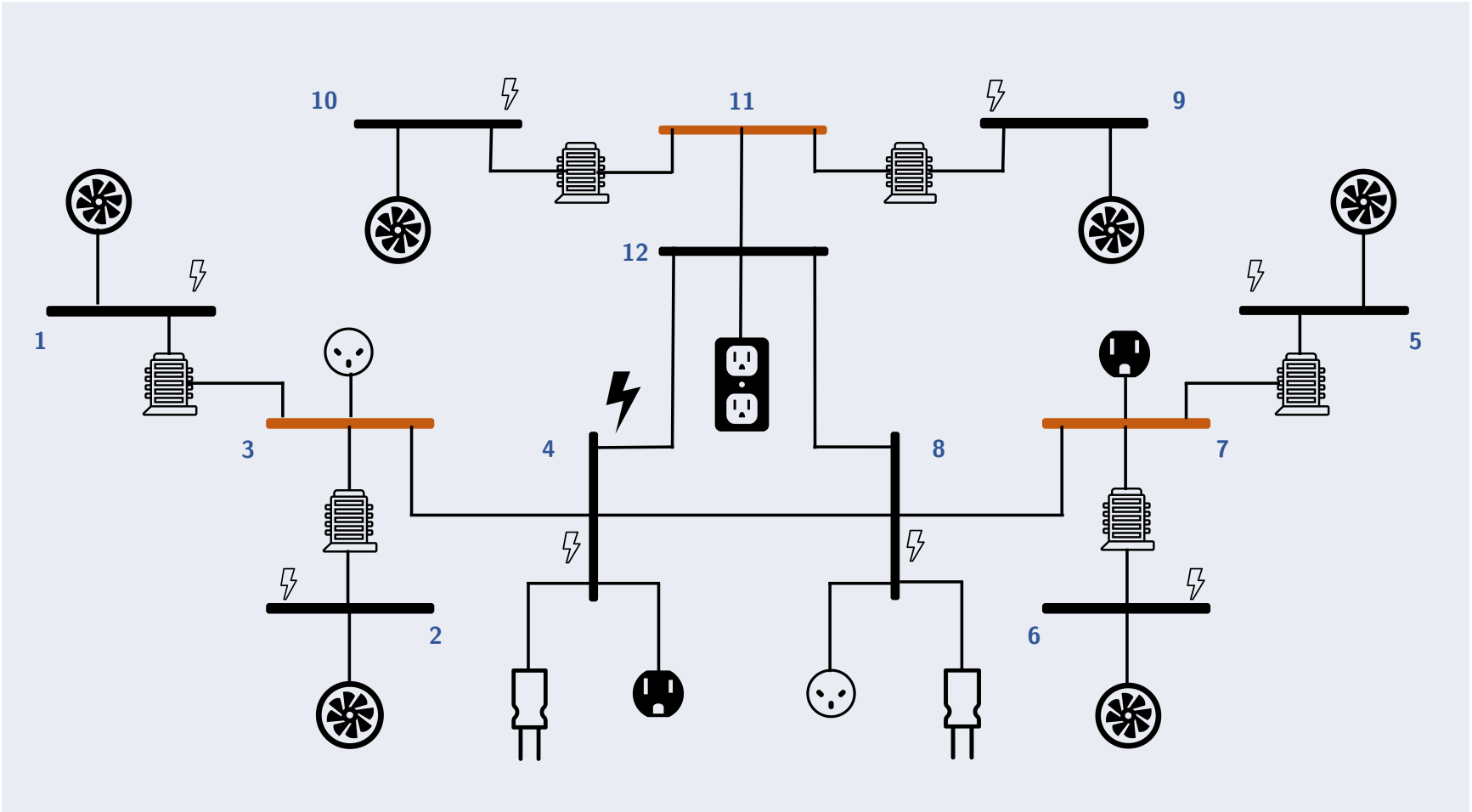
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3. assume knowledge of **disturbance** profile G or go for min-max
4. **gradient-based** approach: scalable, can handle constraints, suboptimal
5. **complexity** of gradient computation $\mathcal{O}(n^3)$ via controllability Gramian

$$L(A+BKC)^\top + (A+BKC)L + GG^\top = \mathbb{O}$$

Modified Kundur case study revisited



Results & insights for case study

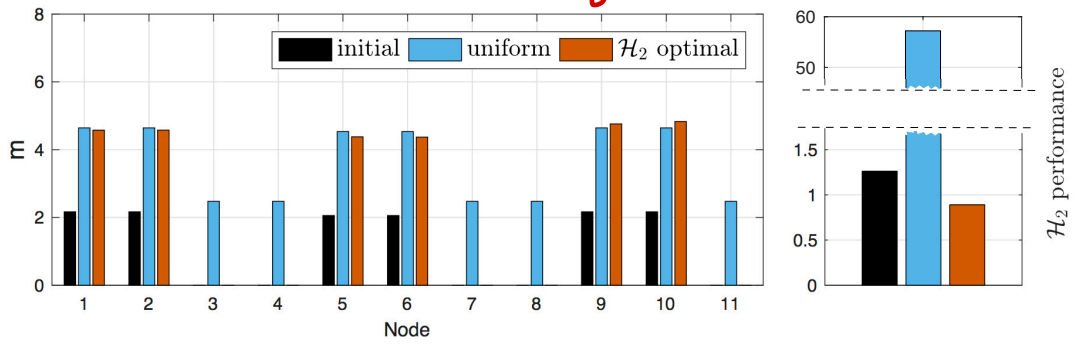
→ it matters { where you allocate / how you tune

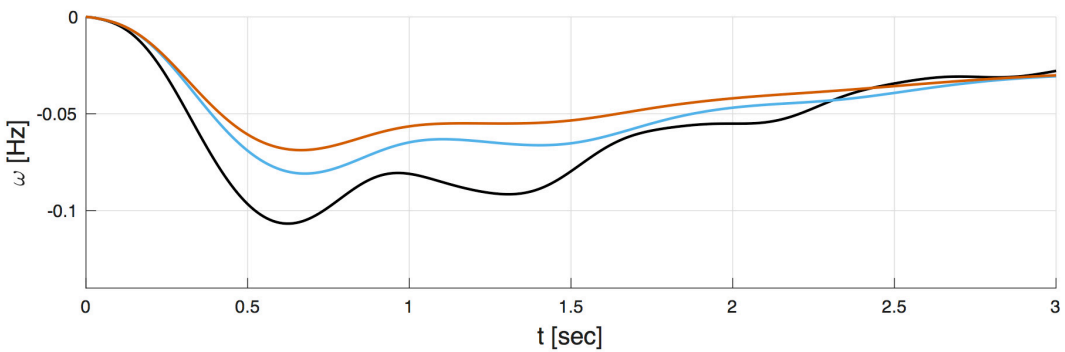
optimal allocation:

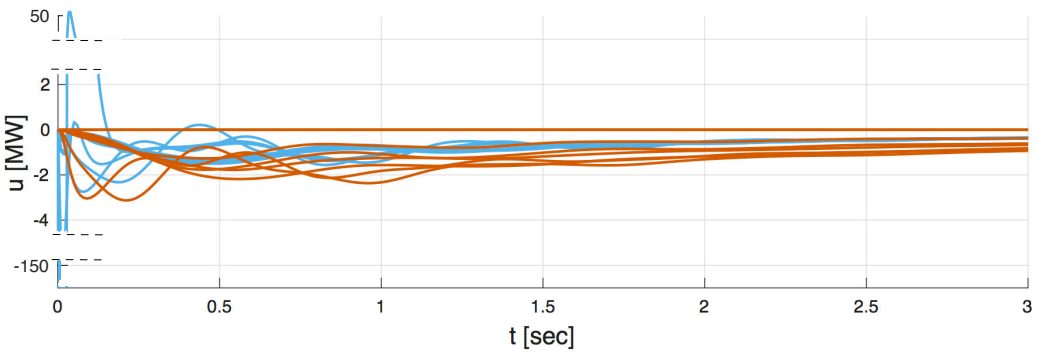
- location of inertia & damping matters
- outperforms heuristic uniform allocation
- need penalty on droop control effort
- power constraint results in $\tilde{D} \approx 2\tilde{M}$

fault at bus #4:

- strong reduction of frequency deviation
- much less control effort than heuristic







Starting from here much more can be said

- suboptimize alternative performance **metrics**: $\mathcal{H}_\infty$, ℓ_1, spectrum
- **analytic insights** for stylistic swing equation model

$$M\ddot{\theta} + D\dot{\theta} + L\theta = \eta$$

$\Rightarrow$ optimal virtual inertia allocation matches disturbance

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Primary Control Effort Under Fluctuating Power Generation in Realistic High-Voltage Power Networks

Melvyn Tyloo and Philippe Jacquod, *Member, IEEE*

Global Analysis of Synchronization Performance for Power Systems: Bridging the Theory-Practice Gap

Fernando Paganini, *Fellow, IEEE*, and Enrique Mallada, *Senior Member, IEEE*

Optimal Placement of Virtual Inertia in Power Grids

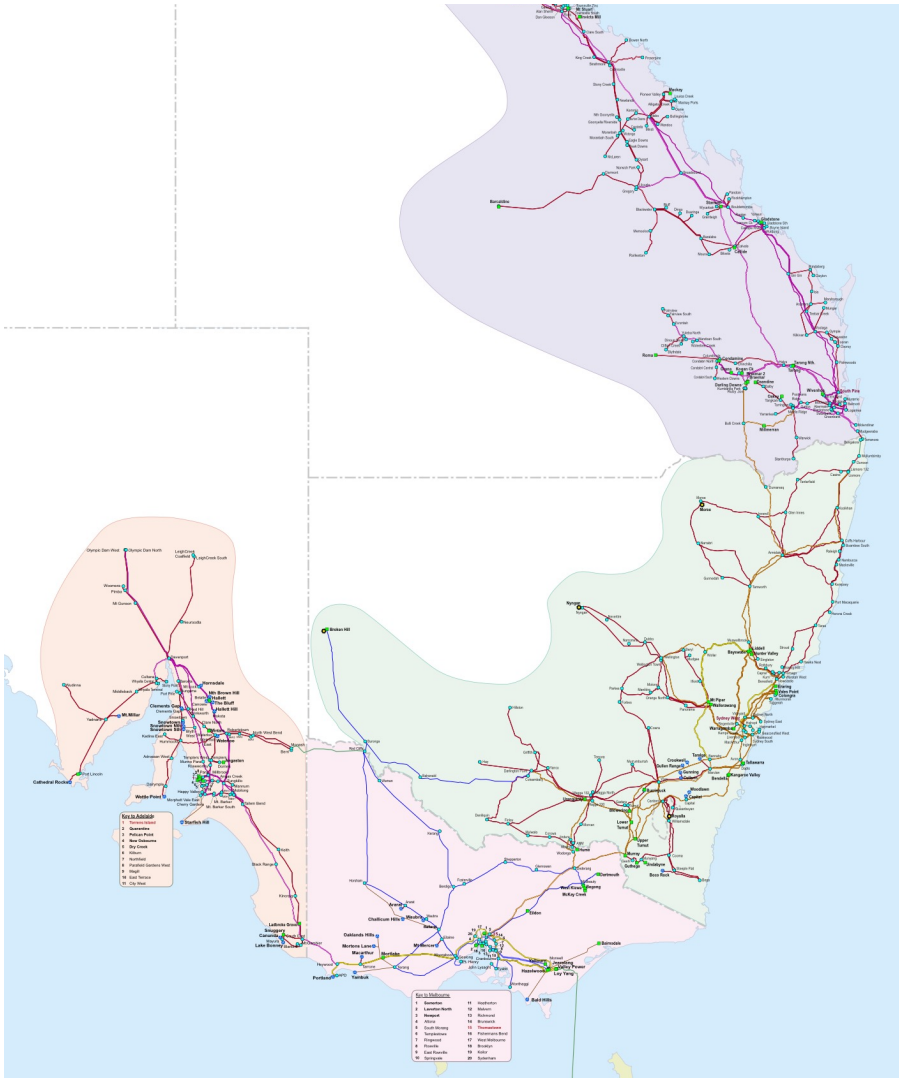
Bala Kameshwar Poolla, Saverio Bolognani, and Florian Dörfler

The Price of Synchrony: Evaluating the Resistive Losses in Synchronizing Power Networks

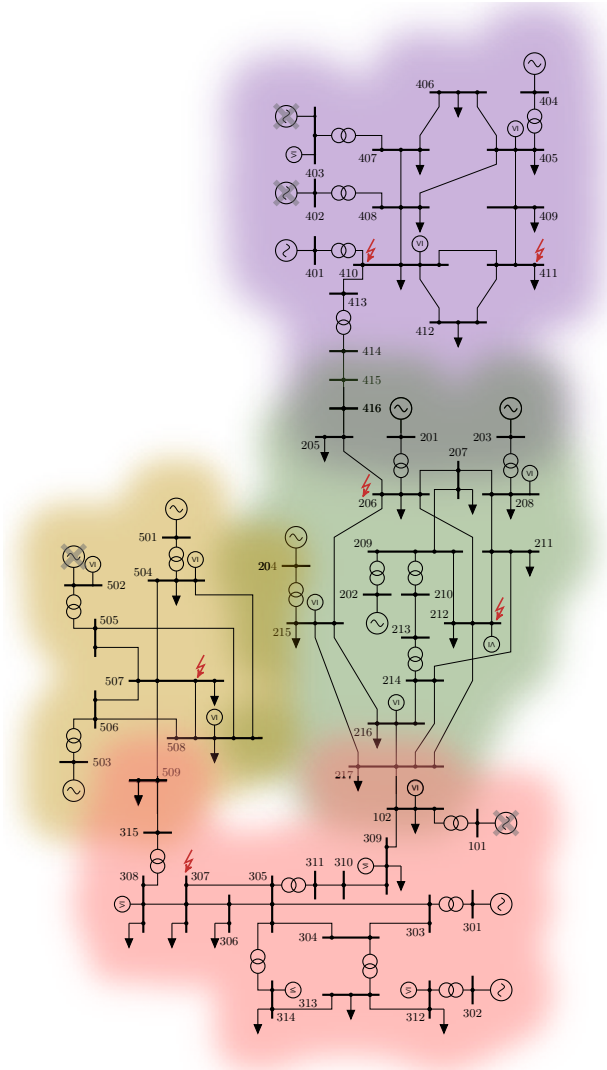
Emma Tegling, Bassam Bamieh, *Fellow, IEEE*, and Dennice F. Gayme, *Senior Member, IEEE*

can we make this control design strategy useful ?

Case-study: South-East Australian Grid



grid topology



simulink model

Case-study: South-East Australian Grid

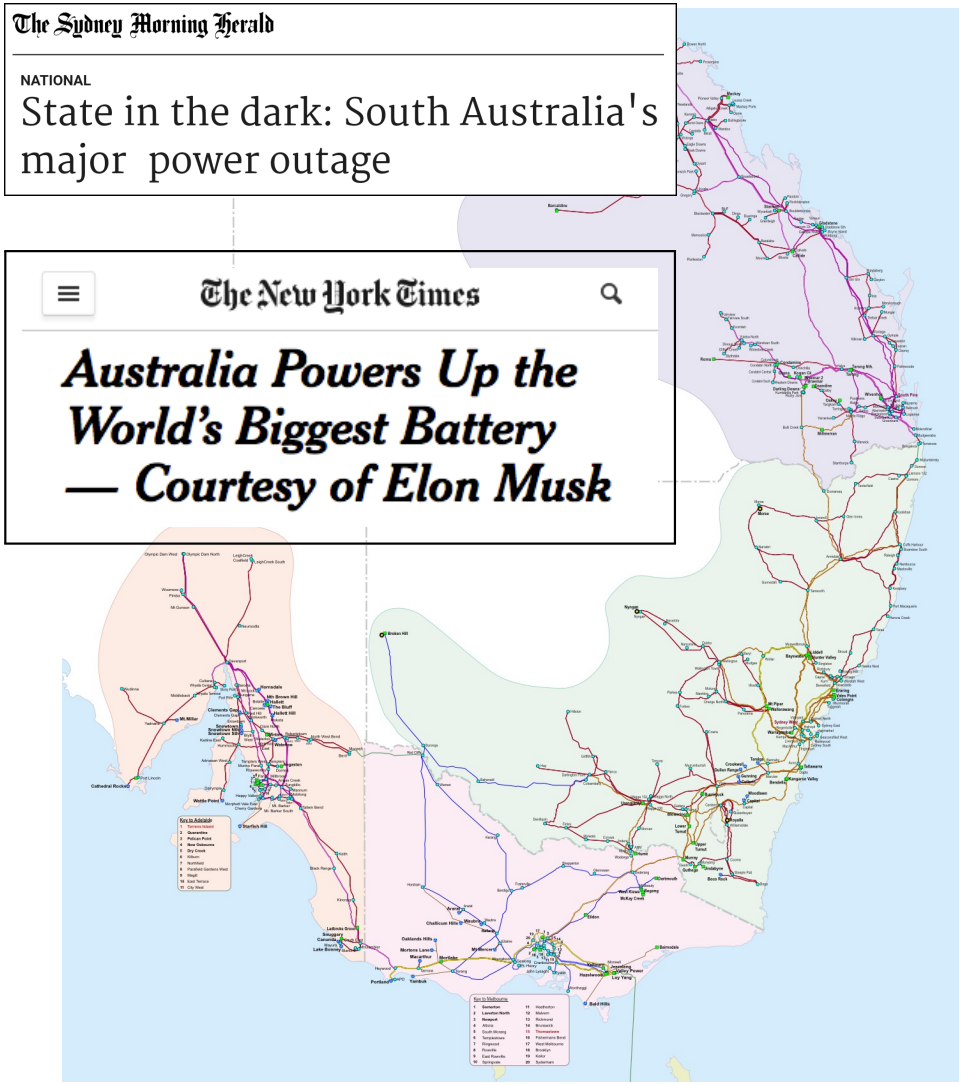
The Sydney Morning Herald

NATIONAL

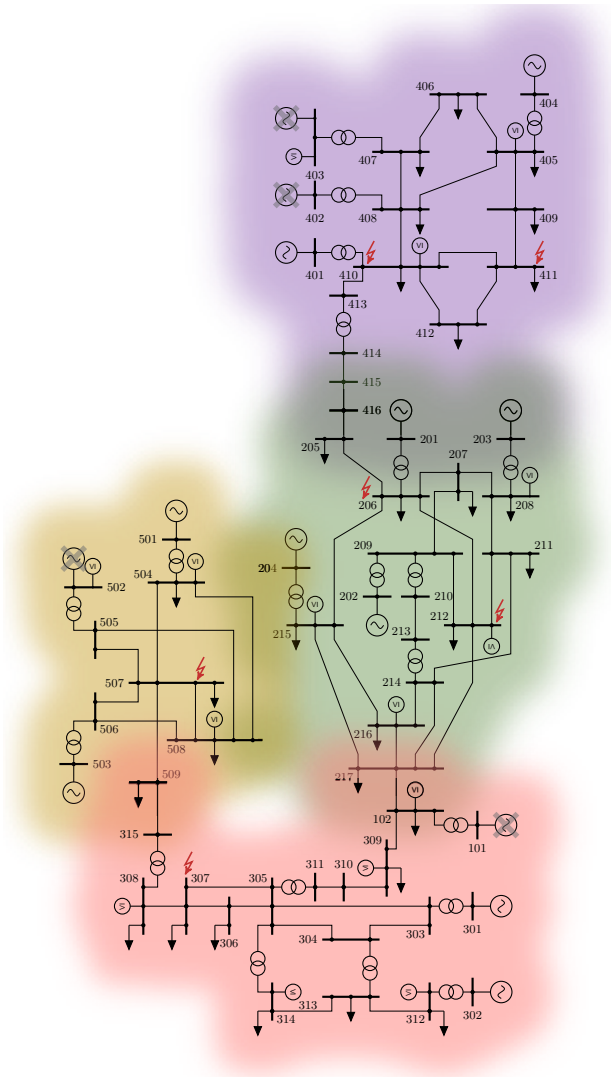
State in the dark: South Australia's major power outage

The New York Times

Australia Powers Up the World's Biggest Battery — Courtesy of Elon Musk



grid topology



simulink model

Closed-loop simulations

non-linear model

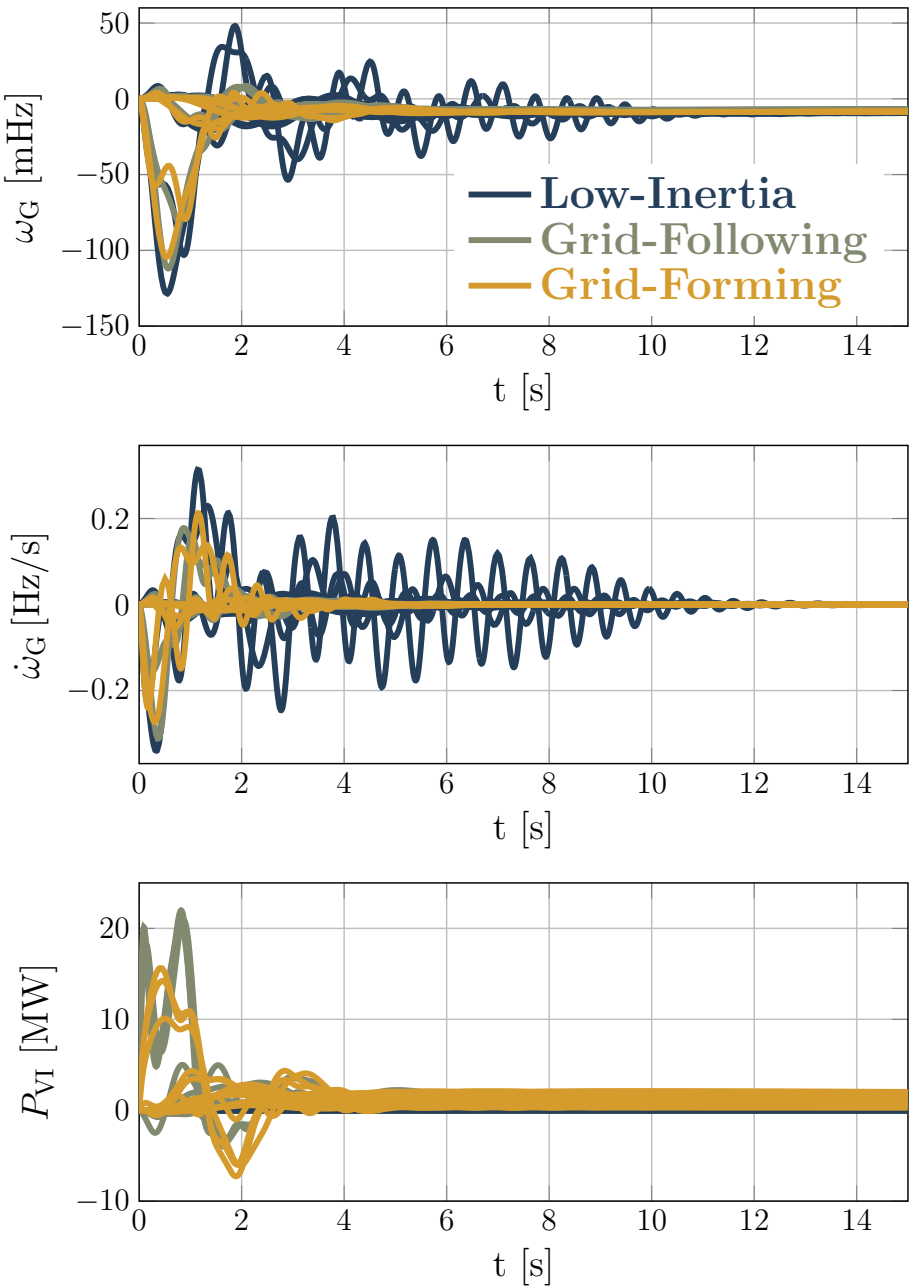
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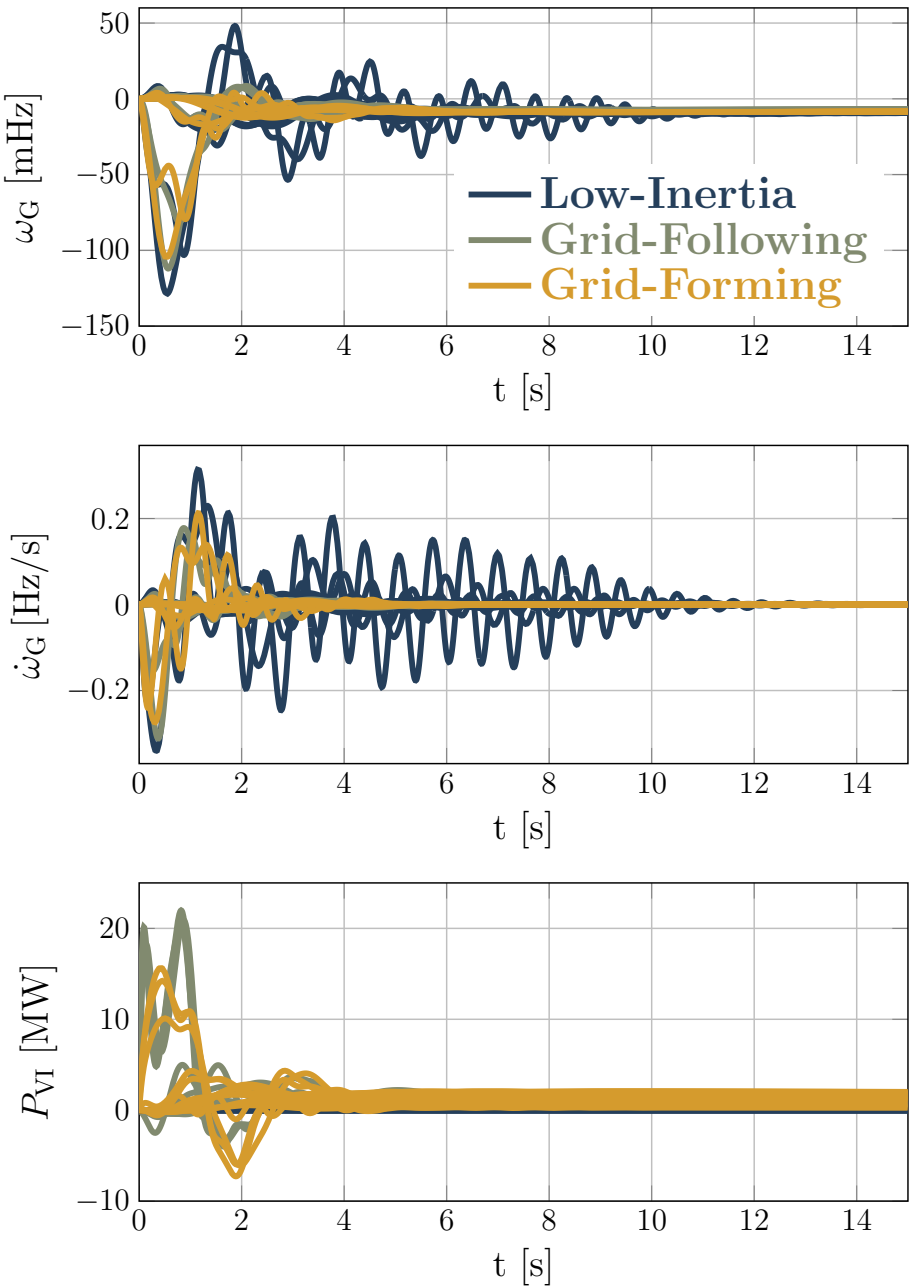
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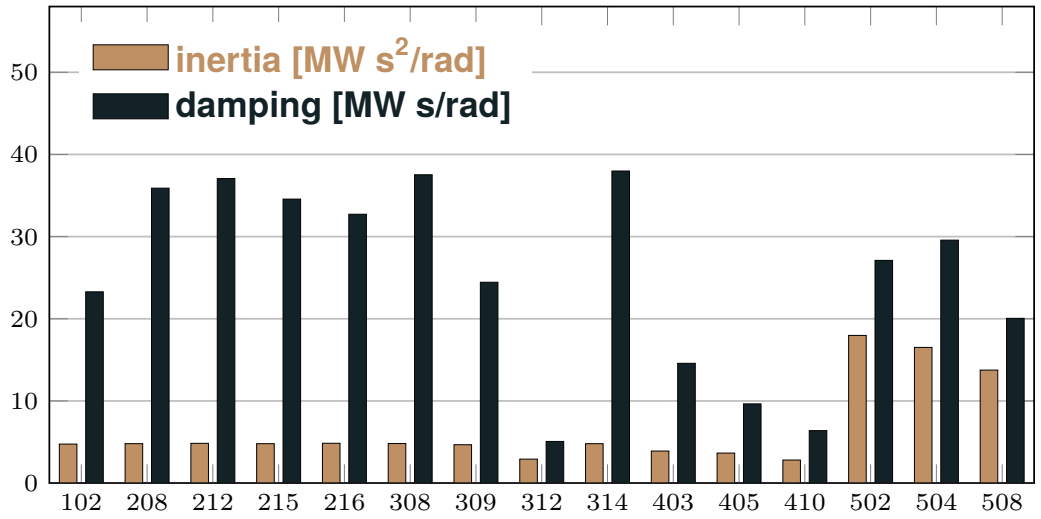
observations

→ system-level optimization **makes a difference** (even at same inertia)

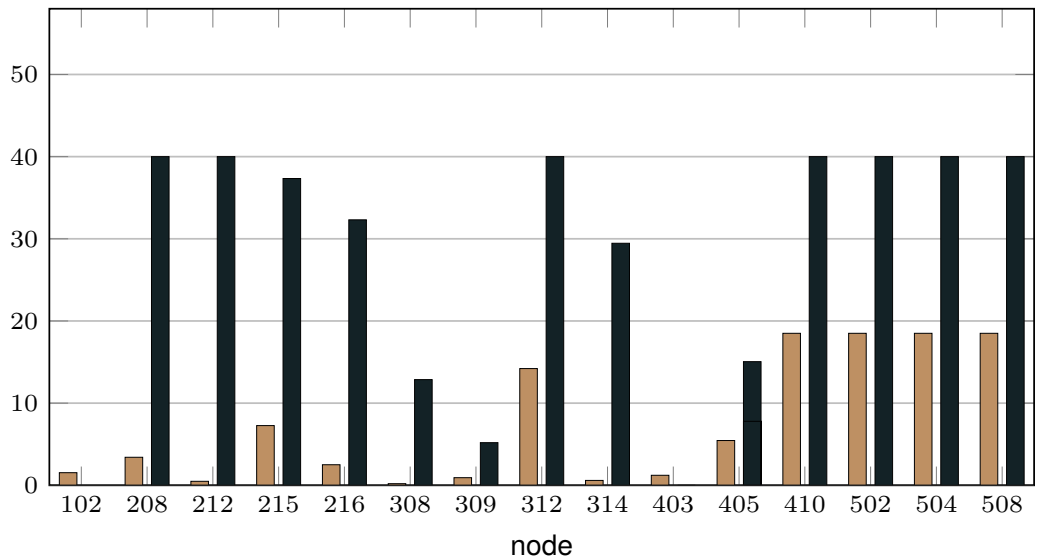
→ forming vs. following: **signal causality** has major impacts (e.g., peak power)

Optimal allocation of virtual inertia/damping

(a) Grid-Forming



(b) Grid-Following

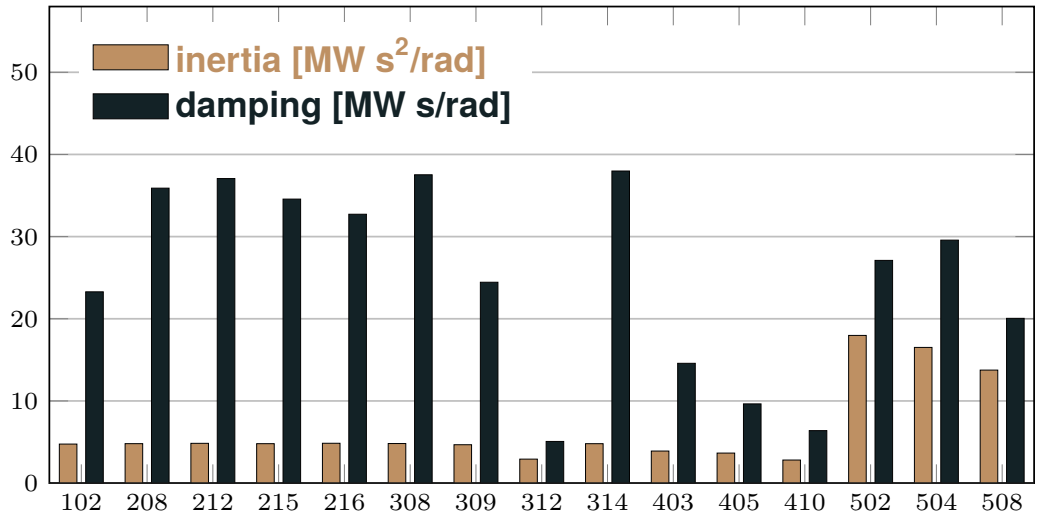


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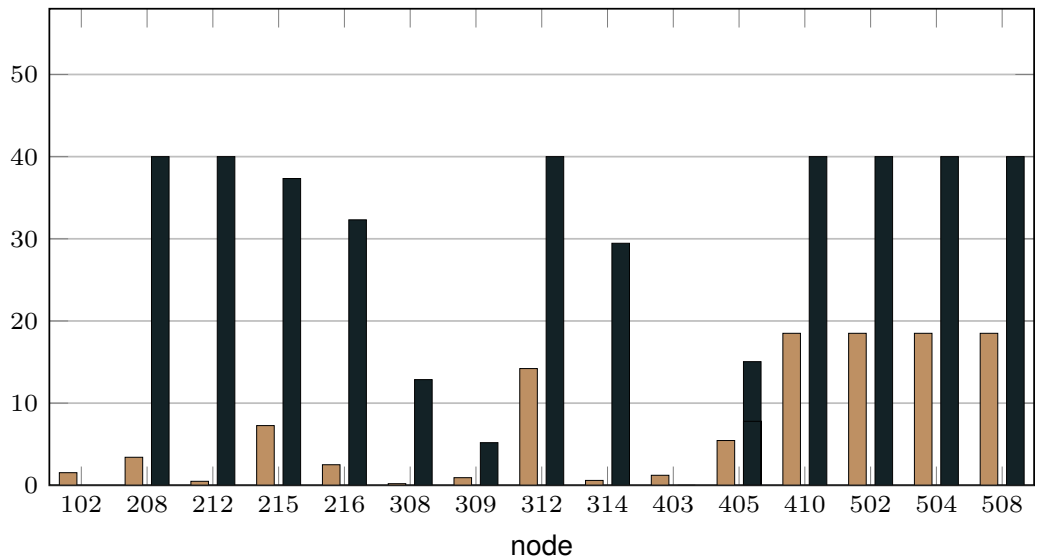
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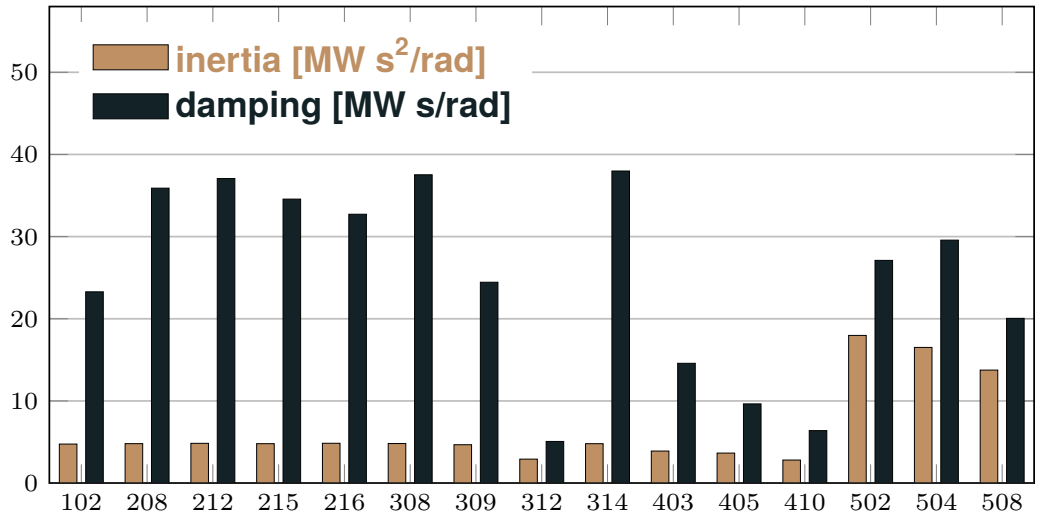


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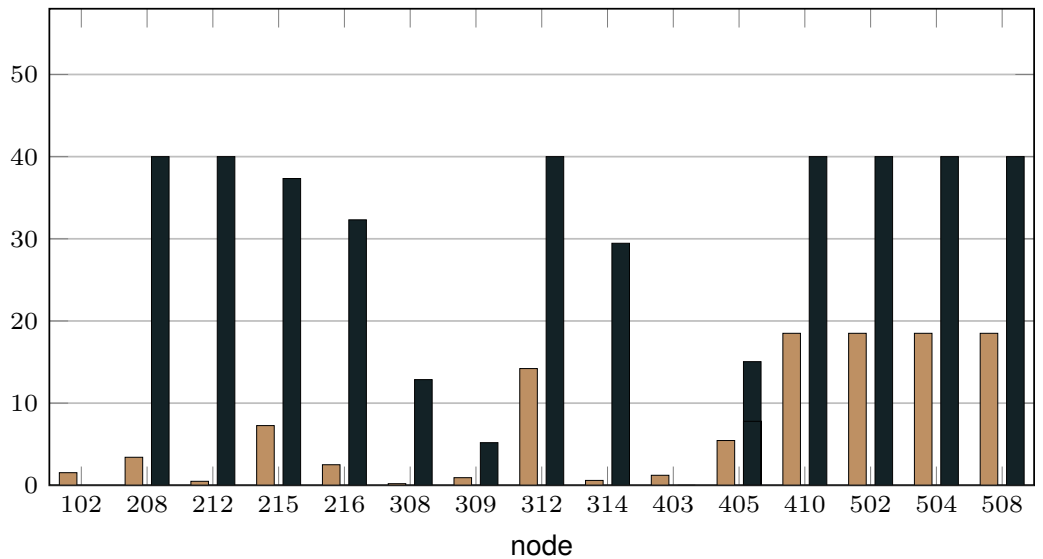
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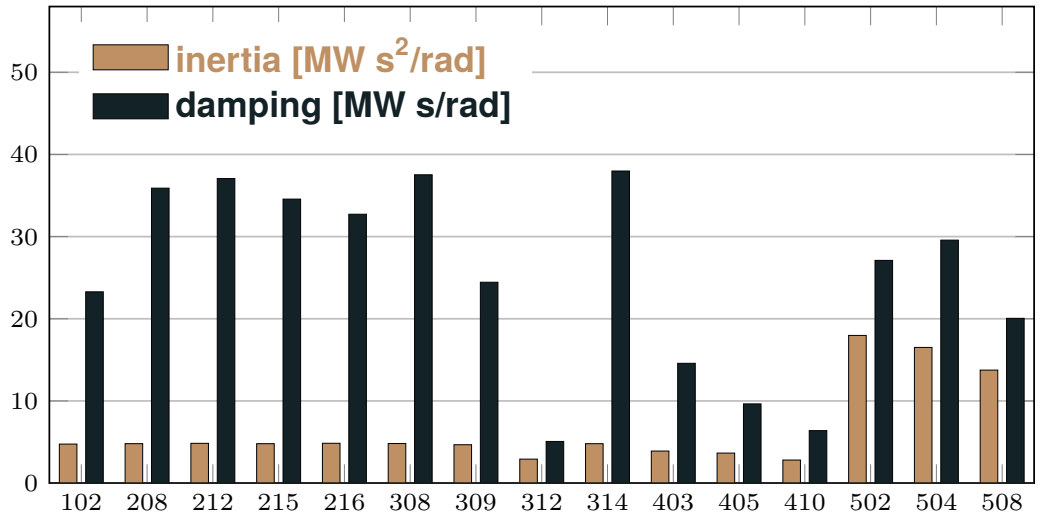
further conclusions

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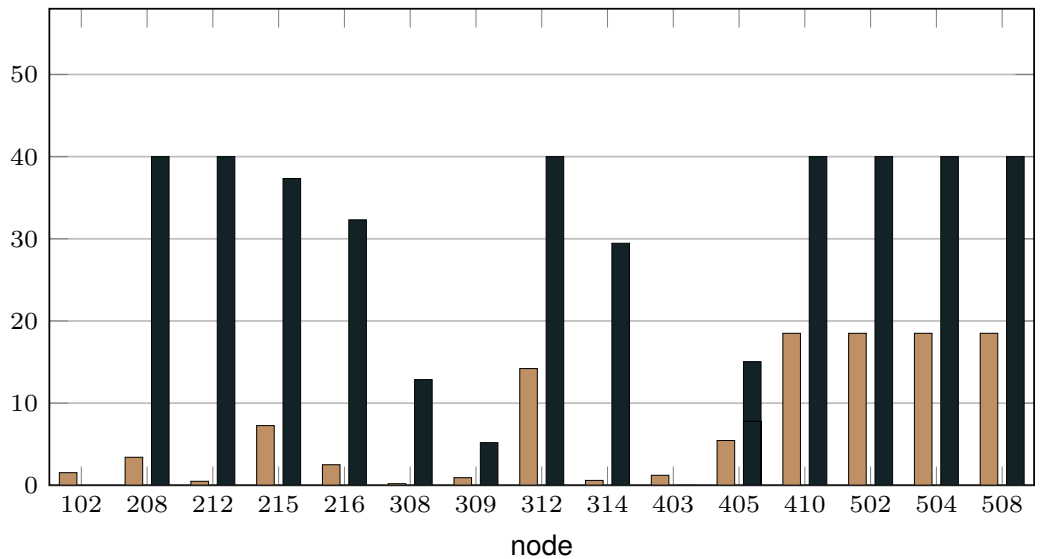
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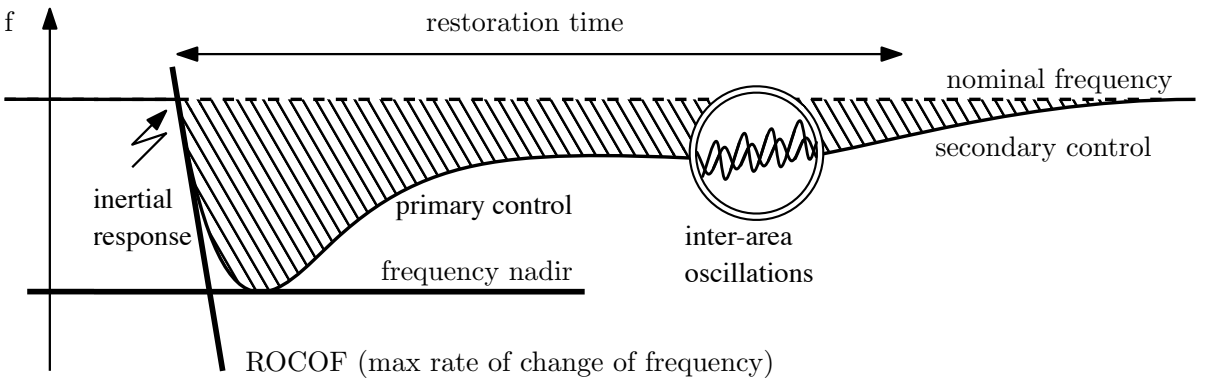
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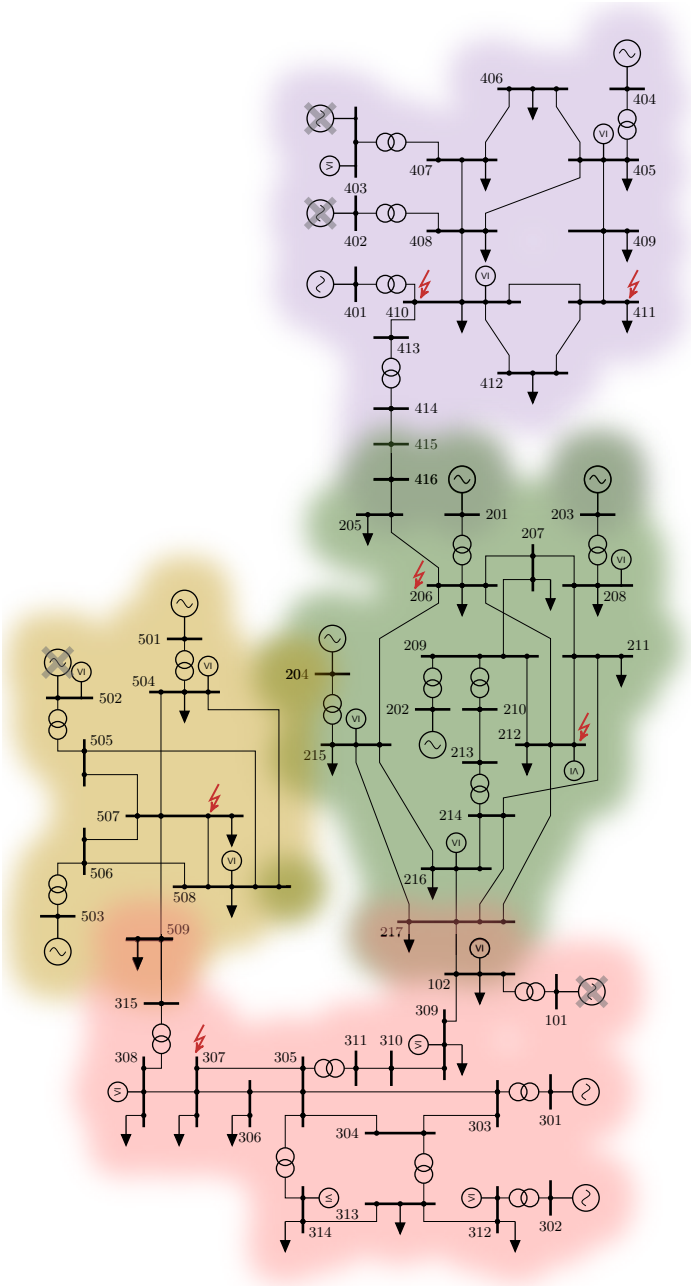
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$\rightarrow$ implications for pricing & markets

Summary: system-level optimization

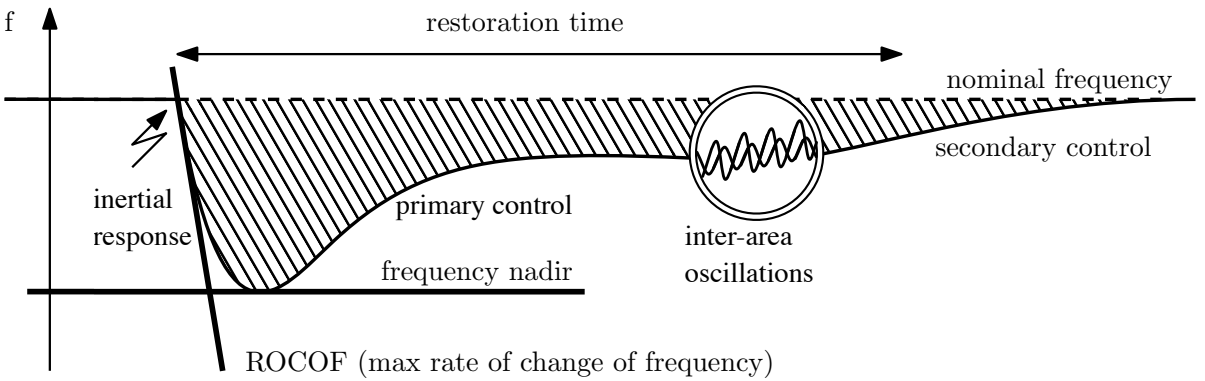
system-level sizing, allocation, & tuning of converter control to minimize amplification of shocks:



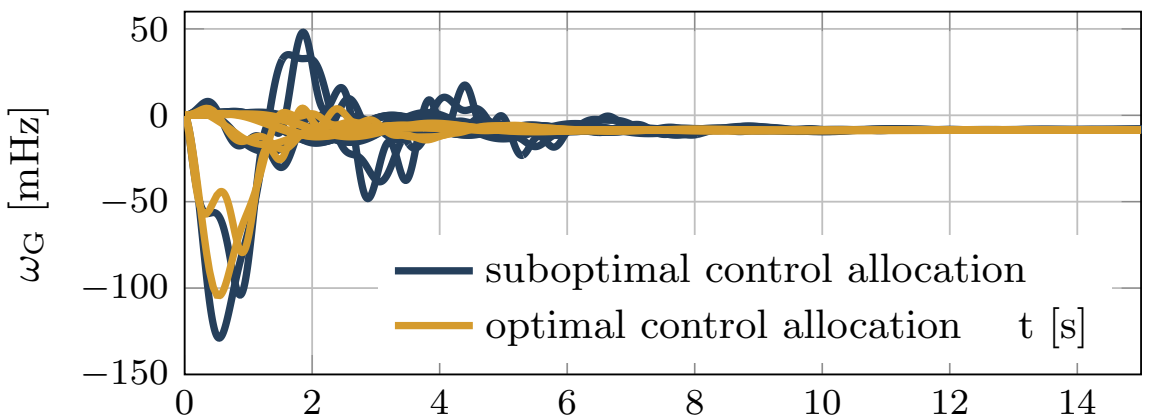


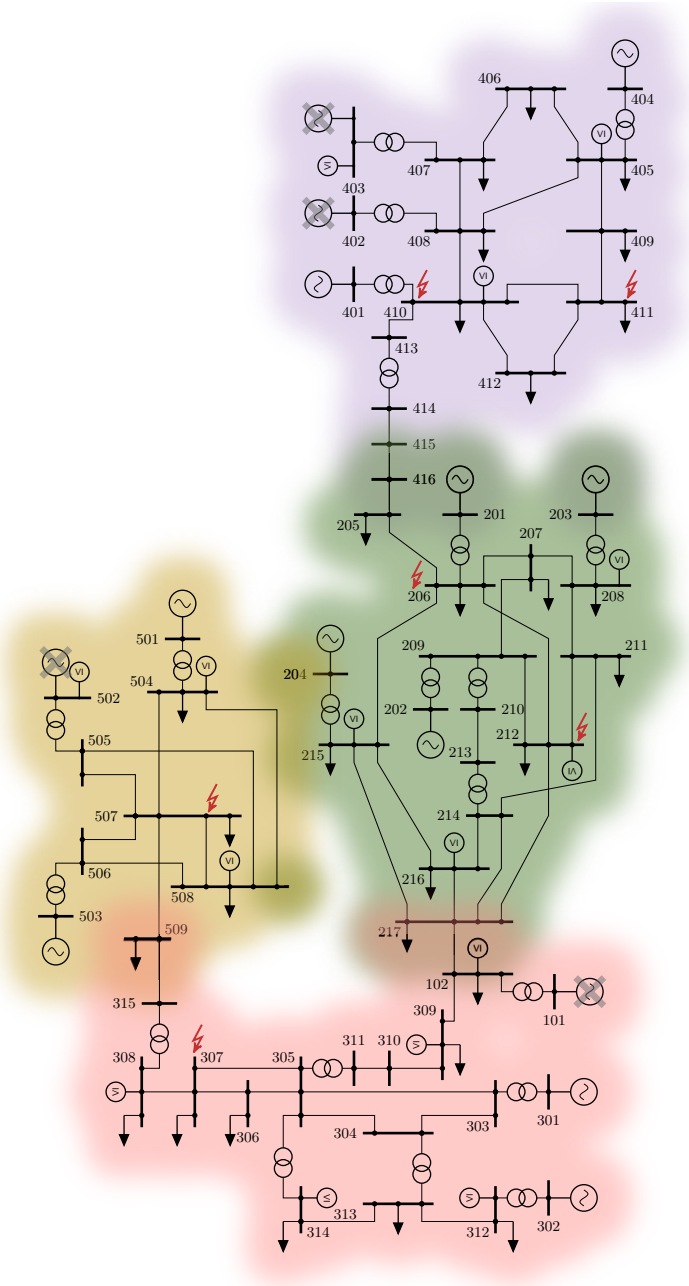
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→ **total inertia/damping** has little effect; rather **sizing, tuning, & spatial allocation** matters





Initial condition for further reading

Placement and Implementation of Grid-Forming and Grid-Following Virtual Inertia and Fast Frequency Response

Bala Kameshwar Poolla, *Student Member, IEEE*, Dominic Groß, *Member, IEEE*, and Florian Dörfler, *Member, IEEE*

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some of basic questions settled $\rightarrow$ now lots of **emergent literature** on

- virtual inertia placement & implementation schemes
- integration limits: how much inertia? how many forming units? where?
- inertia pricing, markets, & security-constrained dispatch
- more general fast-frequency response services
- . . . still a lot more questions than answers

Outline

- Motivation: low-inertia systems are not(?) all about inertia
- Preliminary insights on aggregated system level
- System-level performance metrics
- Optimal allocation & tuning of virtual inertia
- Ancillary services provided by dynamic virtual power plants

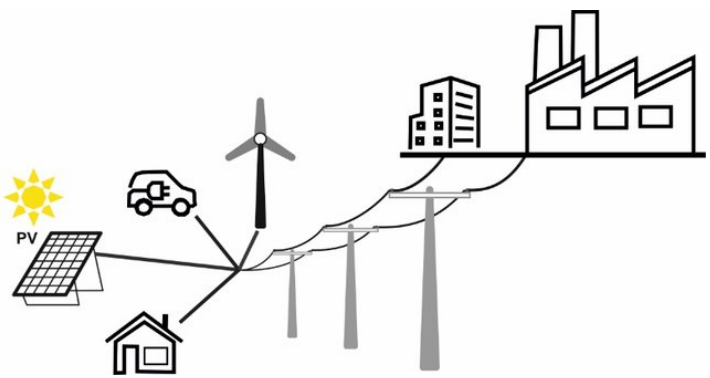
Recall: challenges in future systems

- **conventional power systems**
  - dispatchable generation
  - significant inertial response
  - fast frequency & voltage control

  provided by bulk rotational generation

- **future power systems**
  - variable generation
  - reduced inertia levels
  - ancillary services for frequency & voltage

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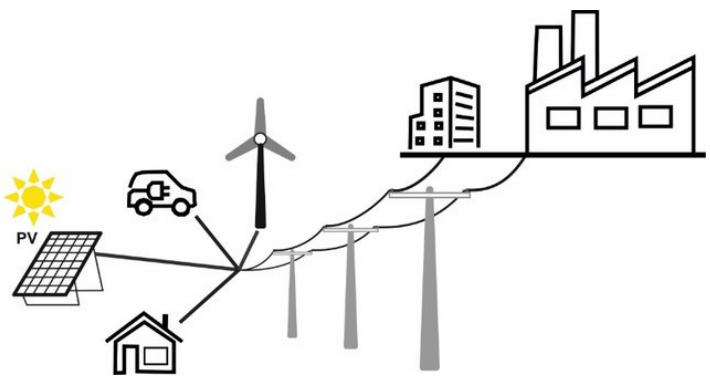
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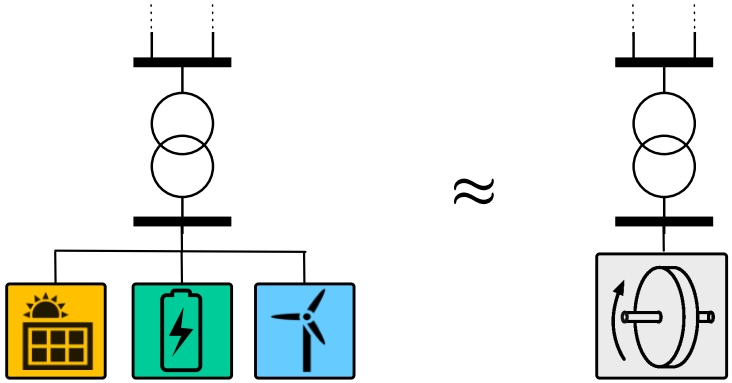
  provided by distributed energy resources

- some of the manifold **challenges**
  - **grid fragility:** intermittency & uncertainty of renewables & reduced inertia levels
  - **device fragility:** converter-interfaced DERs limited in energy, power, fault currents, ...
  - **ancillary services** on faster time scales & shouldered by distributed sources



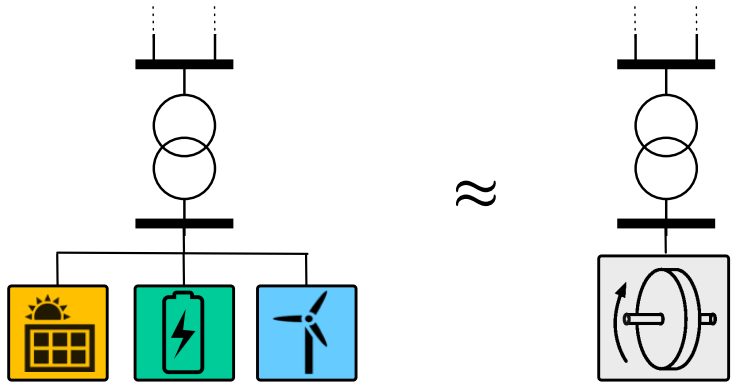
Dynamic Virtual Power Plant (DVPP)

DVPP: coordinate a heterogeneous ensemble of distributed energy resources (DERs) to collectively provide dynamic ancillary services



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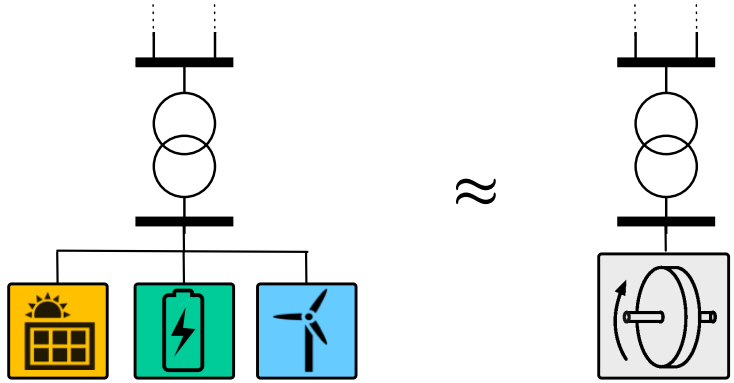
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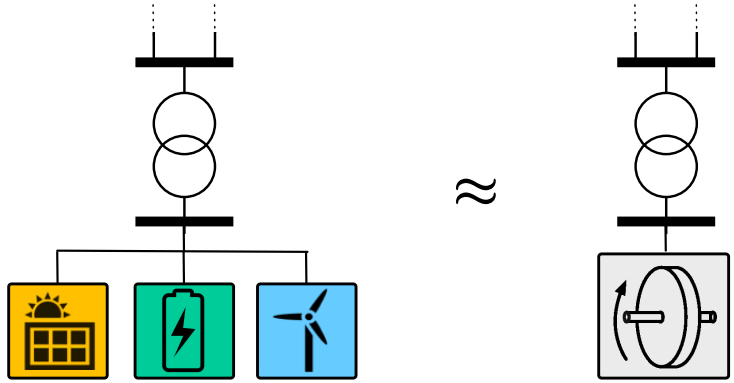
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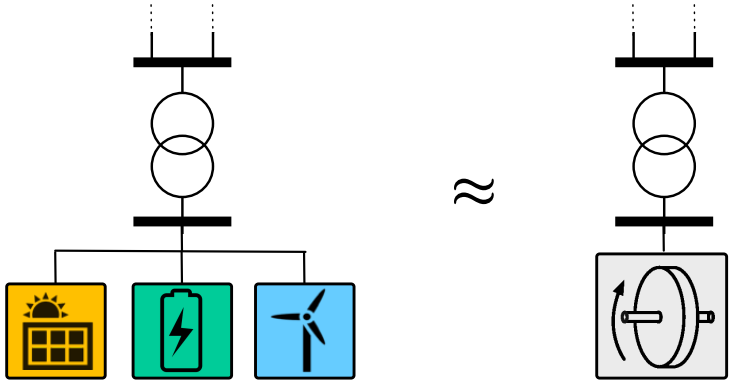
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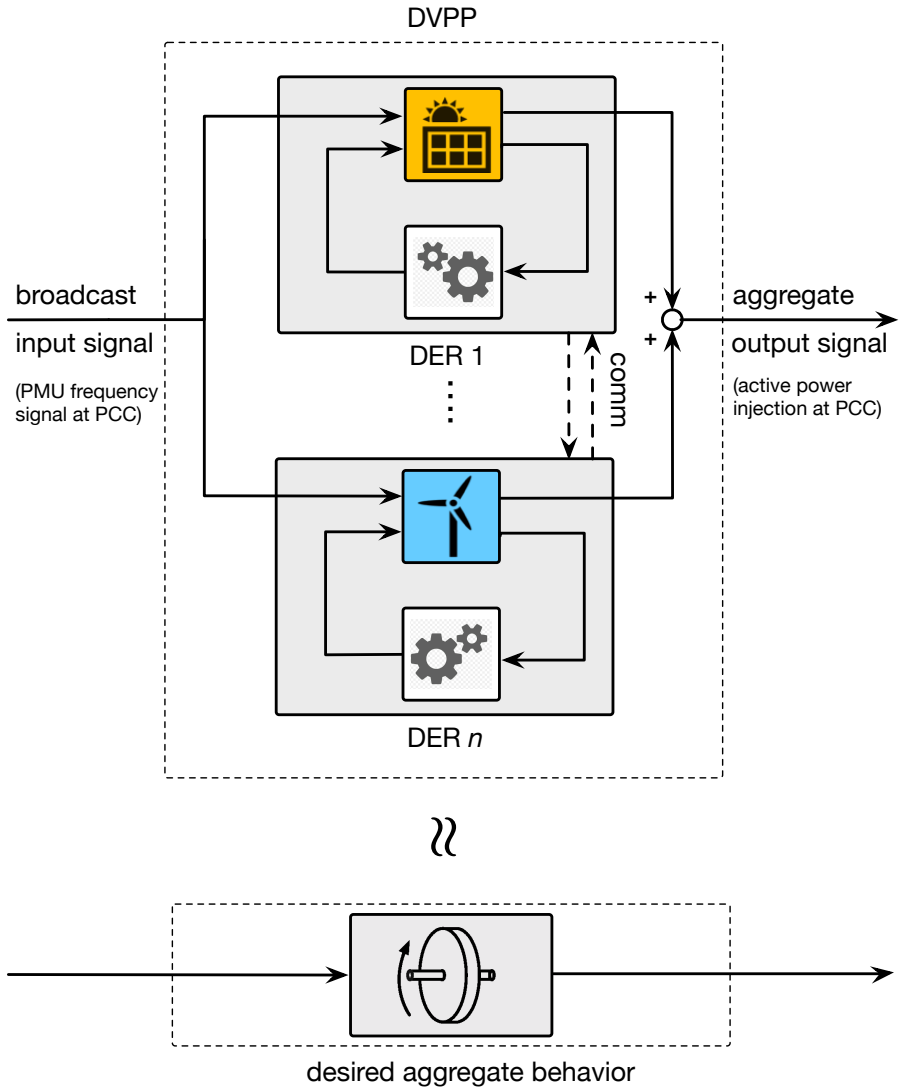
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motivating examples

- frequency control provided by non-minimum phase hydro & on-site batteries (for fast response)
- wind providing fast frequency response & voltage support augmented with storage to recharge turbine
- hybrid power plants, e.g., PV + battery + supercap
- load/generation aggregators . . .

Abstraction: coordinated model matching

- **setup** (simplified): DVPP consisting of
  - DERs connected at a common bus
  - PMU frequency measurement at PCC broadcasted to all DERs

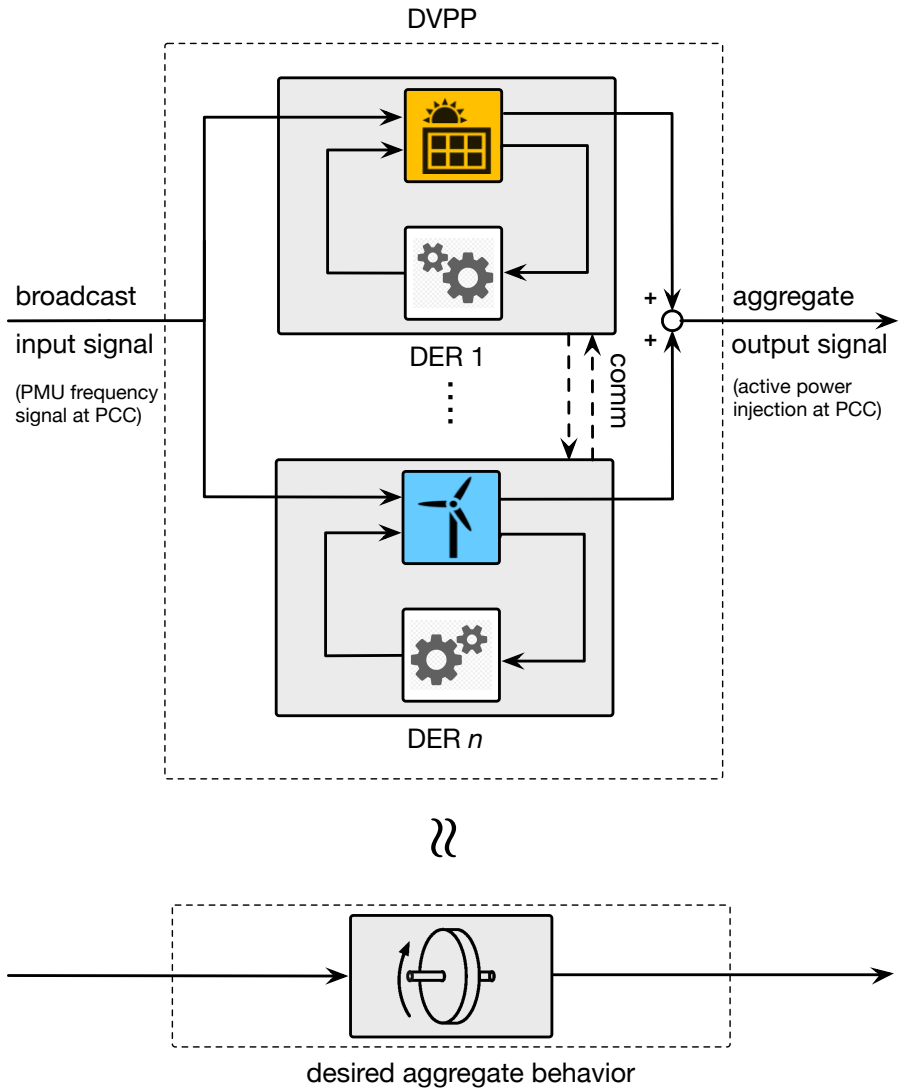


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    power = $\left(H\,s + D\right) \cdot$ *frequency*

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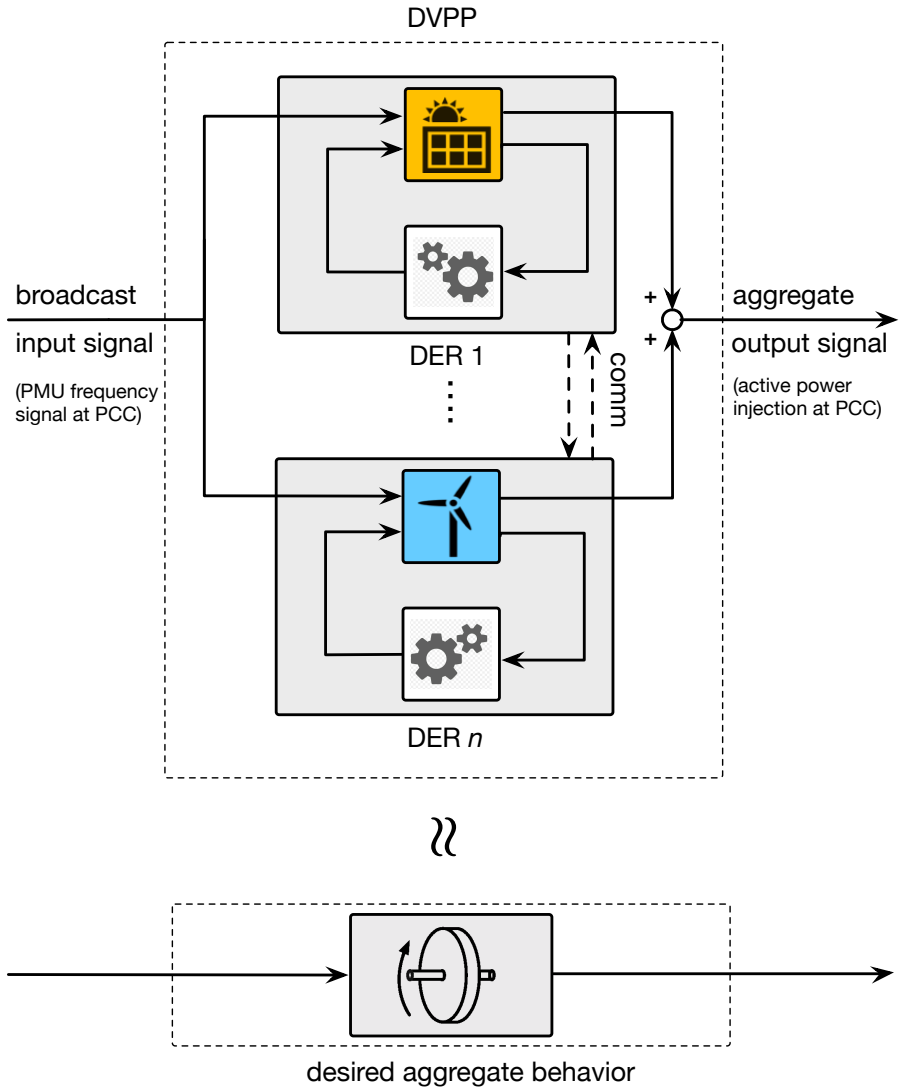
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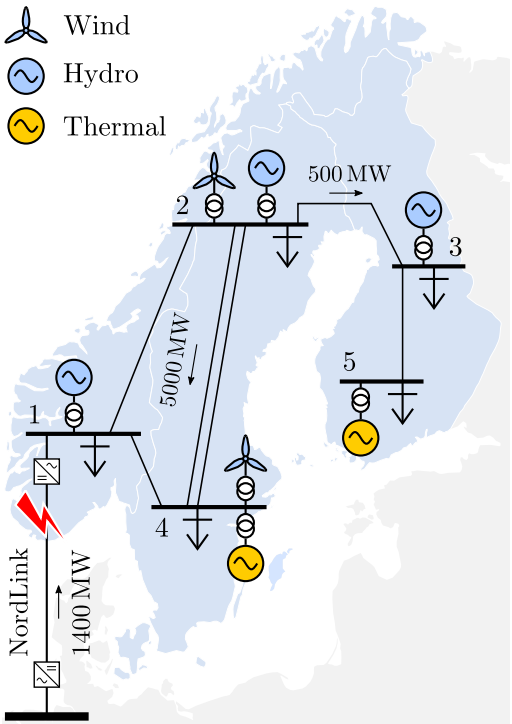
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- task: **coordinated model matching**
  - design decentralized DER controls s.t. aggregate behavior matches specification

    $\sum_i \text{power}_i \;=\; \left(H\,s + D\right) \cdot$ *PMU-frequency*
  - taking device-level constraints into account
  - & online adapting to variable generation



Case study

in collaboration with
J. Björk (Svenska kraftnät)
& K.H. Johansson (KTH)



aggregated 5-bus model of Nordic grid

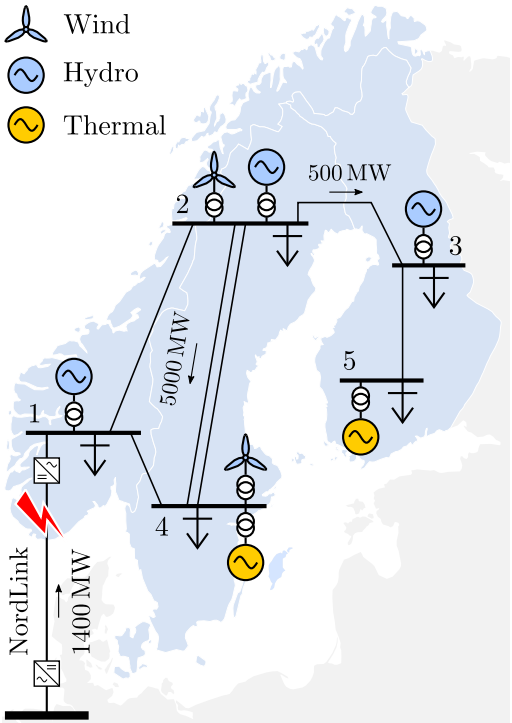
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- **FCR-D service**

  $\rightarrow$ desired behavior

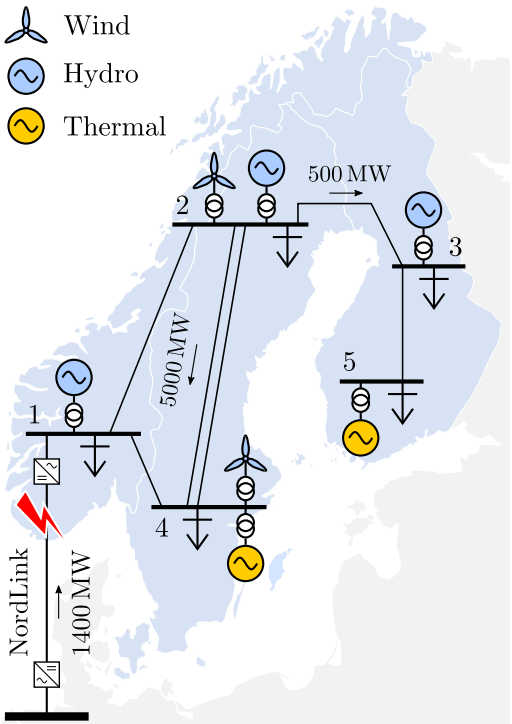
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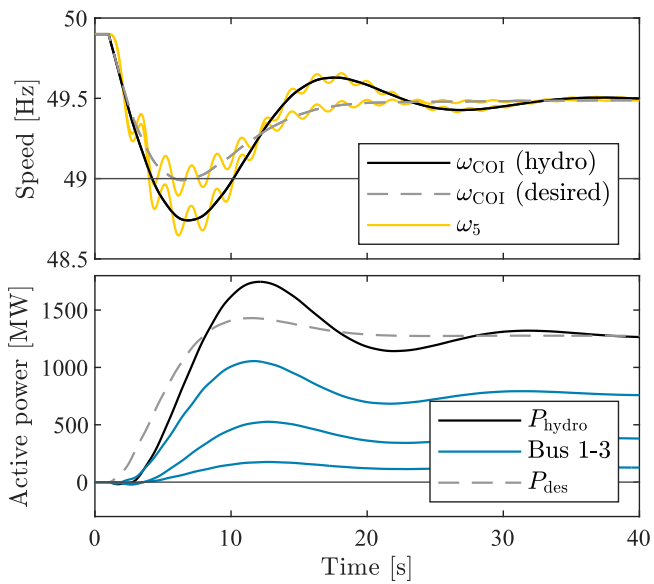
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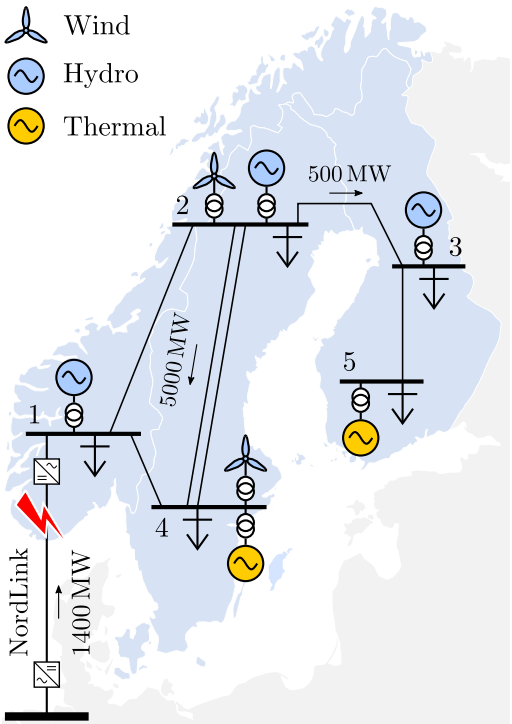
  → inverse response: initial power surge opposes control

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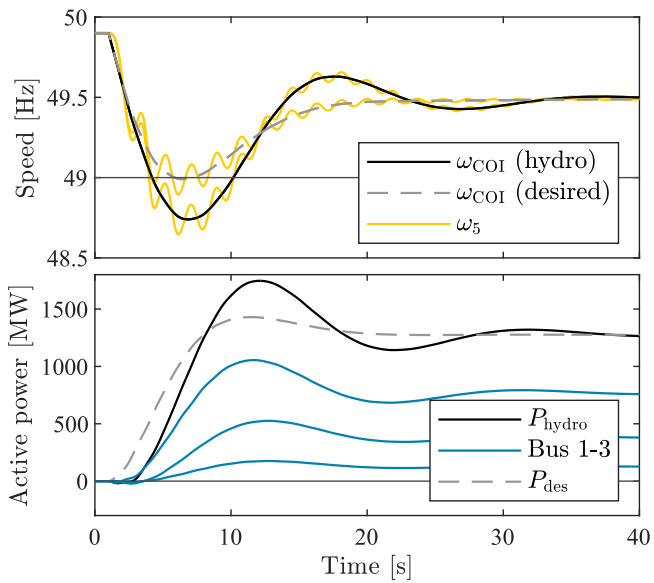


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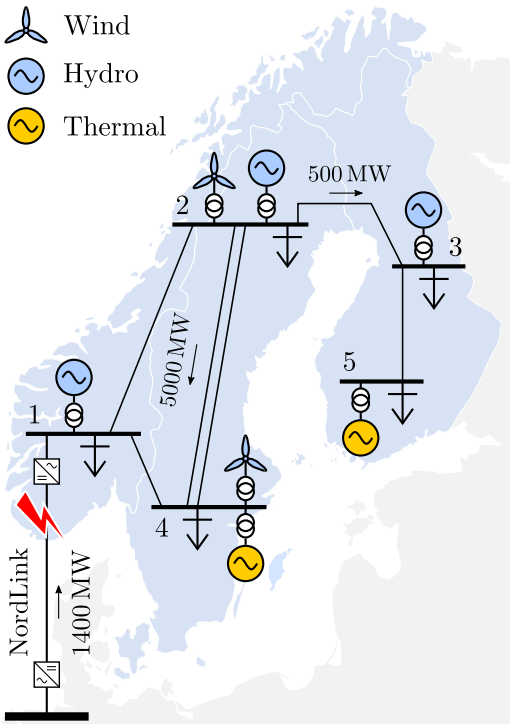
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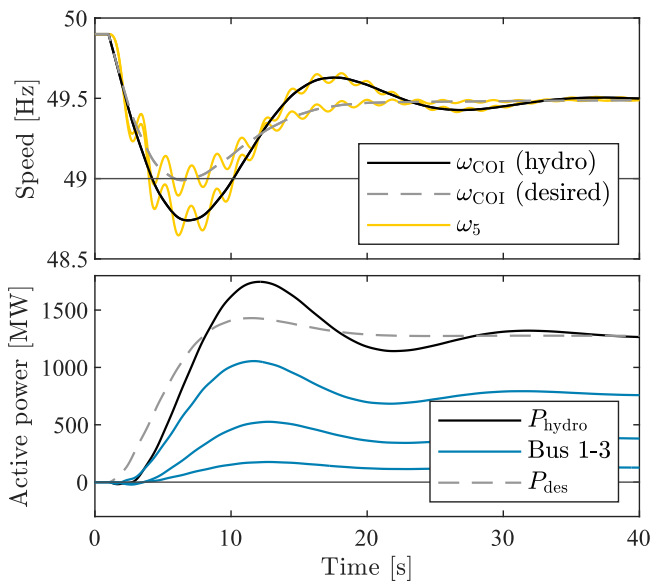


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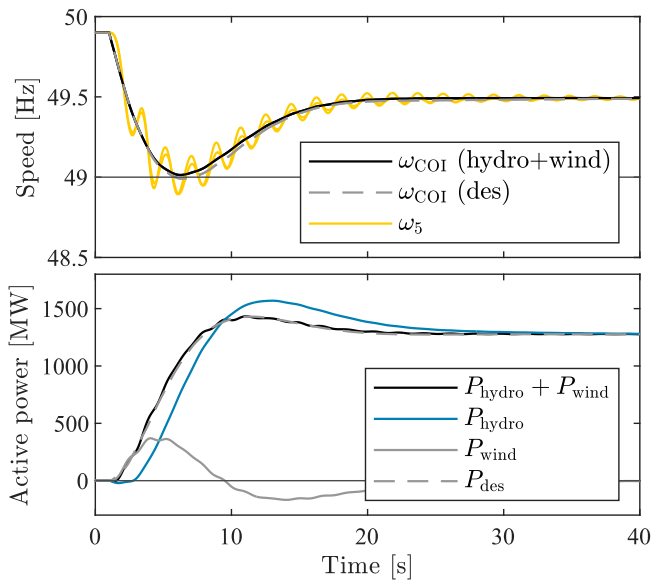
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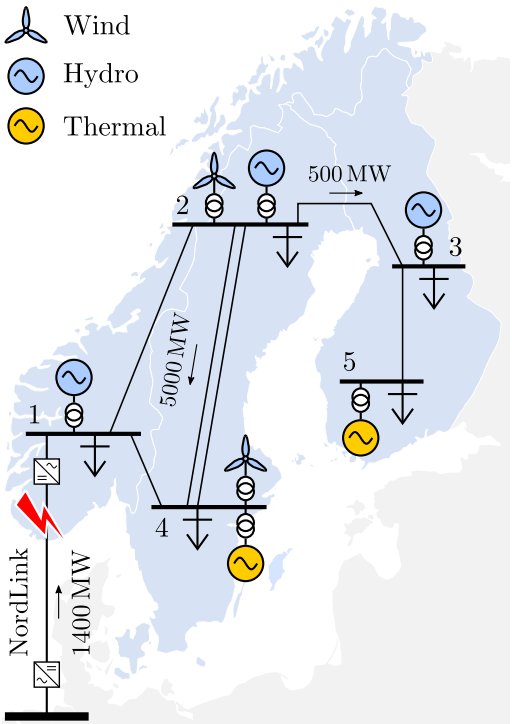
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- better **DVPP solution**: coordinate hydro & wind to cover all time scales



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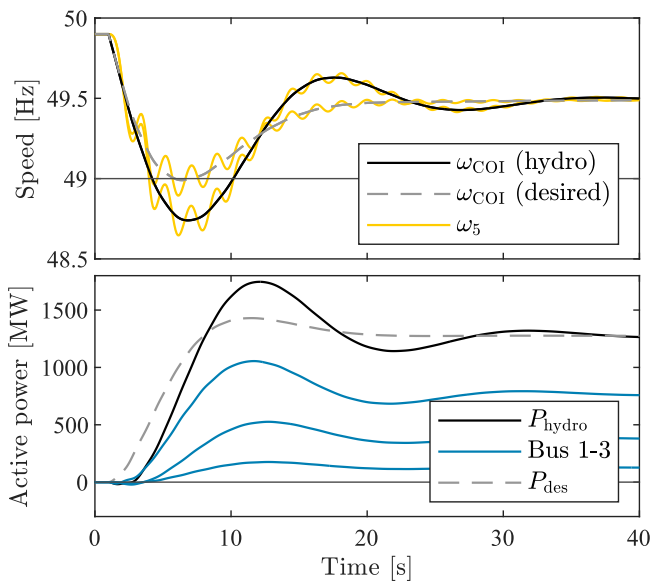


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- **FCR-D service**
  → desired behavior

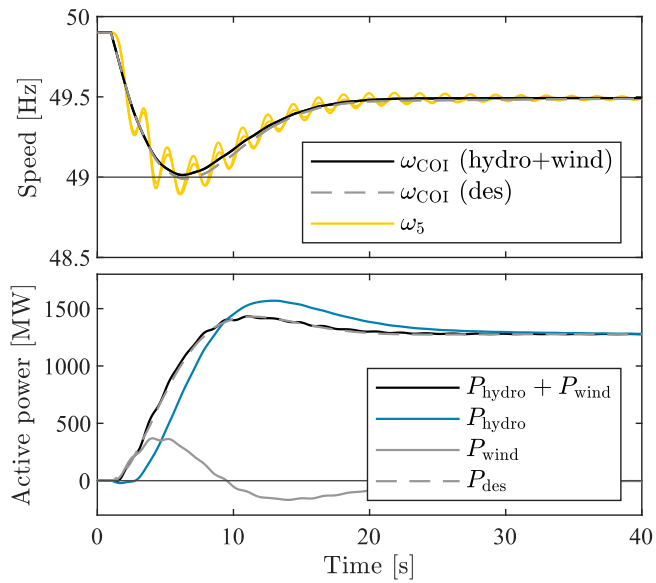
$$\frac{\textit{power}}{\textit{frequency}} = \frac{3100\cdot(6.5s+1)}{(2s+1)(17s+1)}$$

- well-known **issue:** actuation of hydro power via governor is non-minimumphase
  → inverse response: initial power surge opposes control
  → unsatisfactory response



- **discussed solution**: augment hydro with batteries for fast response
  → hybrid plant solution works but not economic

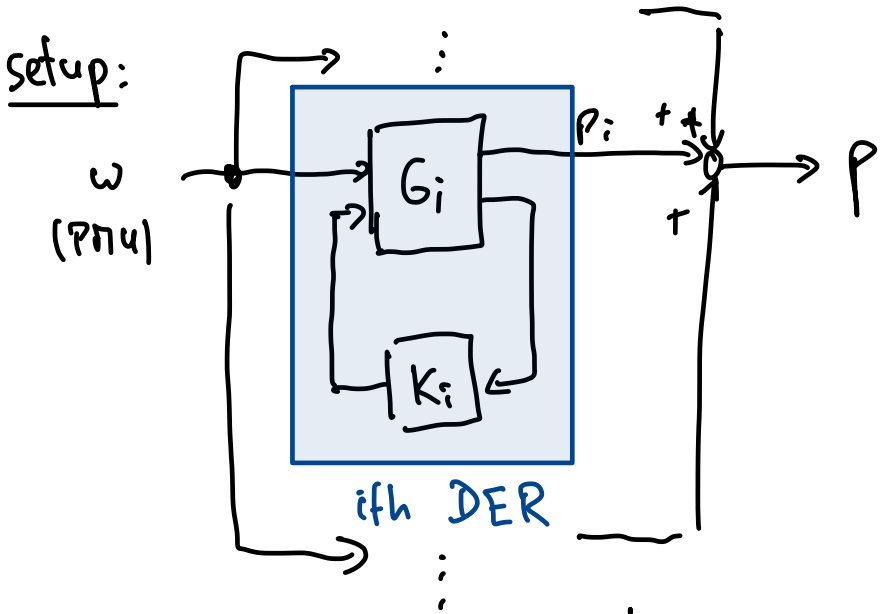
- better **DVPP solution**: coordinate hydro & wind to cover all time scales



next up: **how** to do it ?

DVPP Control Design

(covered on the board)



aggregate behavior: $p = \sum_{i=1}^{n} p_i$

$= \sum_{i=1}^{n} T_i(s) \cdot \omega$

$T_i(s) = \dfrac{G_i(s)\, K_i(s)}{1 + G_i(s)\, K_i(s)}$

$\dfrac{\Pi_s + D}{T_s + \uparrow}$

desired aggregate behavior: $p = T_{des}(s) \cdot \omega$

$\sum T_i = T_{des}$

→ dynamic participation factor $m_i(s)$ to disaggregate the spec

taking device-level constraints into account: bandwidth, peak, zeros, ...

Example: low-pass filter for slow devices participating in steady-state regulation, band-pass for devices offering a transient response

→ $T_i(s) = T_{des}(s) \cdot m_i(s)$ ← choose K_i to track this behavior

constraint: $\sum m_i(s) = 1$

Starting point for further reading

Dynamic Virtual Power Plant Design for Fast Frequency Reserves: Coordinating Hydro and Wind

Joakim Björk, *Student Member, IEEE,* Karl Henrik Johansson, *Fellow, IEEE,* and Florian Dörfler, *Senior Member, IEEE*

***Abstract*—To ensure frequency stability in future low-inertia power grids, fast ancillary services such as fast frequency reserves (FFR) have been proposed. In this work, the coordination of conventional (slow) frequency containment reserves (FCR) with FFR is treated as a decentralized model matching problem. The design results in a dynamic virtual power plant (DVPP) whose aggregated output fulfills the system operator (SO) requirements in all time scales, while accounting for the capacity and bandwidth limitation of participating devices. This is illustrated in a 5-machine representation of the Nordic synchronous grid. In the Nordic grid, stability issues and bandwidth limitations associated with non-minimum phase zeros of hydropower is a well-known problem. By simulating the disconnection of a 1400 MW importing dc link, it is shown that the proposed DVPP design allows for coordinating fast FFR from wind, with slow FCR from hydro, while respecting dynamic limitations of all participating devices. The SO requirements are fulfilled in a realistic low-inertia scenario without the need to install battery storage or to waste wind energy by curtailing the wind turbines.**

generation and other small-scale producers to participate in frequency containment reserves (FCR) [4].

Virtual power plants (VPPs), aggregating together groups of small-scale producers and consumers, is a proposed solution to allow smaller players with more variable production to enter into the market with the functionality of a larger conventional power plant [1], [5], [6]. The main objectives are to coordinate dispatch, maximize the revenue, and to reduce the financial risk of variable generation, in the day-ahead and intra-day markets [7], [8]. But also other services, such as voltage regulation [9] and allocation of FCR resources [10]–[12] have been proposed.

In this work, we design controllers that coordinate FCR over all time scales, beyond mere set-point tracking, forming a dynamic virtual power plant (DVPP) offering dynamic ancillary services [13]. While none of the individual devices may be able to provide FCR consistently across all power and energy levels or over all time scales, a sufficiently

Control Design of Dynamic Virtual Power Plants: An Adaptive Divide-and-Conquer Approach

Verena Häberle, Michael W. Fisher, Eduardo Prieto-Araujo and Florian Dörfler

***Abstract*—In this paper, we present a novel control approach for dynamic virtual power plants (DVPPs). In particular, we consider a group of heterogeneous distributed energy resources (DERs) which collectively provide desired dynamic ancillary services such as fast frequency and voltage control. Our control approach relies on an adaptive divide-and-conquer strategy: first, we disaggregate the desired frequency and voltage control specifications of the aggregate DVPP via adaptive dynamic participation matrices (ADPMs) to obtain the desired local behavior for each device. Second, we design local linear parameter-varying (LPV) $\mathcal{H}_\infty$ controllers to optimally match this local behaviors. In the process, the control design also incorporates the physical and engineered limits of each DVPP device. Furthermore, our adaptive control design can properly respond to fluctuating device capacities, and thus include weather-driven DERs into the DVPP setup. Finally, we demonstrate the effectiveness of our control strategy in a case study based on the IEEE nine-bus system.**

tracking set points. The key to success is heterogeneity: Only a sufficiently heterogeneous group of devices (complementing each other in terms of energy/power availability, response times, and weather dependency) can reliably provide dynamic ancillary services across all power and energy levels and time scales, while none of the individual devices is able to do so.

Motivating examples of collections of heterogeneous energy sources for dynamic ancillary services provision include hydro-power with initially inverse response dynamics compensated by batteries on short time scales [8], synchronous condensers (with rotational energy) paired with converter-based generation [9], or hybrid storage pairing batteries with supercapacitor providing regulation on different frequency ranges [10]. However, the coordination of all these collections is highly customized, and not (even conceptually) extendable

DYNAMIC VIRTUAL POWER PLANT: A NEW CONCEPT FOR GRID INTEGRATION OF RENEWABLE ENERGY SOURCES

A PREPRINT

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Coordinated Control of Virtual Power Plants to Improve Power System Short-Term Dynamics

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Abstract: The paper proposes a coordinated frequency control strategy for Virtual Power Plants (VPPs), with the inclusion of Distributed Energy Resources (DERs), e.g., Solar Photo-Voltaic Generation (SPVG), Wind Generator (WG) as well as Energy Storage System (ESS). The objective is to improve the short-term dynamic response of the overall power system. The robustness of the proposed control is evaluated through a Monte Carlo analysis and a detailed modeling of stochastic disturbances of loads, wind speed, and solar irradiance. The impact of communication delays of a variety of realistic communication networks with different bandwidths is also discussed and evaluated. The case study is based on a modified version of the WSCC 9-bus test system with inclusion of a VPP. This is modeled as a distribution network with inclusion of a variety of DERs.

Conclusions on low-inertia systems

Summary & take-aways

- **changing system characteristics**
  - lower inertia levels & DER intermittency $\rightarrow$ more brittle & fast dynamics
  - revisit modeling: time-scale separation issues & converter-dominated dynamics
- **converter-interfaced generation control**
  - sync via grid-forming vs. following control
  - do not try to emulate the old system!
  - grid-forming controls: nonlinear, constrained, multivariable, & take dc-side into account
- **ancillary services provided by DERs**
  - tuning & spatial allocation of fast-frequency response, i.e., virtual inertia/damping
  - pooling of heterogeneous devices into dynamic virtual plant providing services

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- there is still **a lot to be understood** about modeling, dynamics, control, & operation of low-inertia systems
- these are very exciting times!
  $\rightarrow$ great opportunity for control

