Control of Low-Inertia Power Systems

Florian Dörfler, ETH Zürich

DFG Autumn School @ KIT 2019

(recent) power systems control challenges

→ integration of renewable sources

→ changing generation technology

opportunities:

- converter-interfaced sources

→ fast / modular / flexible actuation

- technological advances

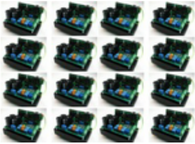
→ sensing / actuation / communication

- scientific advances

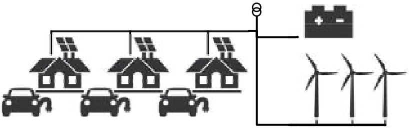
→ control / optimization / learning

⇒ **end-to-end & real-time automation** of cyber-socio-technical power system

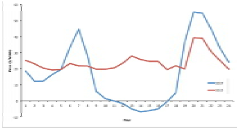
→ scaling



→ distributed generation & prosumption



→ liberalized markets



Replacing the system foundation

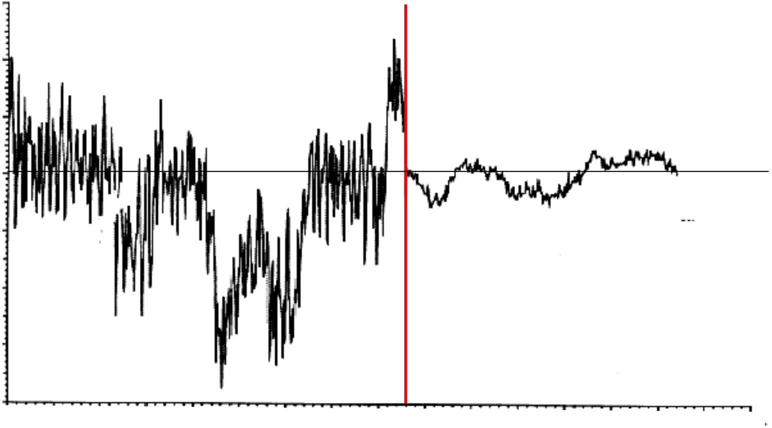
fuel & synchronous machines

- − **not sustainable**
- + **central & dispatchable** generation
- + **large** rotational **inertia** as buffer
- + **self-synchronize** through the **grid**
- + **resilient** voltage / frequency **control**
- − **slow** actuation & **control**

renewables & power electronics

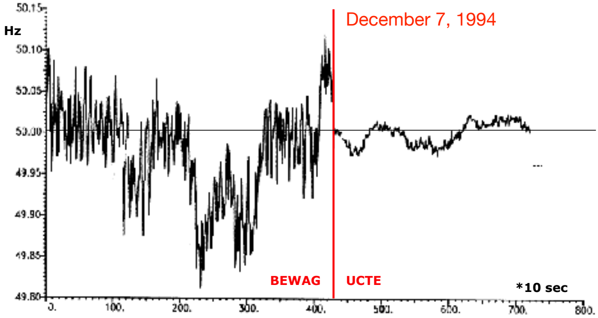
- + **sustainable**
- − **distributed & variable** generation
- − almost **no energy storage**
- − **no** inherent **self-synchronization**
- − **fragile** voltage / frequency **control**
- + **fast / flexible / modular control**

What do we see here ?



West Berlin re-connecting to Europe

Source: *Energie-Museum Berlin*



before re-connection: islanded operation based on **batteries** & boiler

afterwards connected to European grid & **synchronous generation**

The concerns are not hypothetical

issues broadly recognized by system operators, device manufacturers, & academia

theguardian

South Australia

South Australia blackout: entire state left without power after storms

key events

- storm damages two lines
- control not resilient loss of 500 MW wind power
- between lines: conventional grid would have survived

obstacle to sustainability

- integrating power electronics
- robust & resilient control

Critically re-visit modeling/analysis/control

Foundations and Challenges of Low-Inertia Systems

(Invited Paper)

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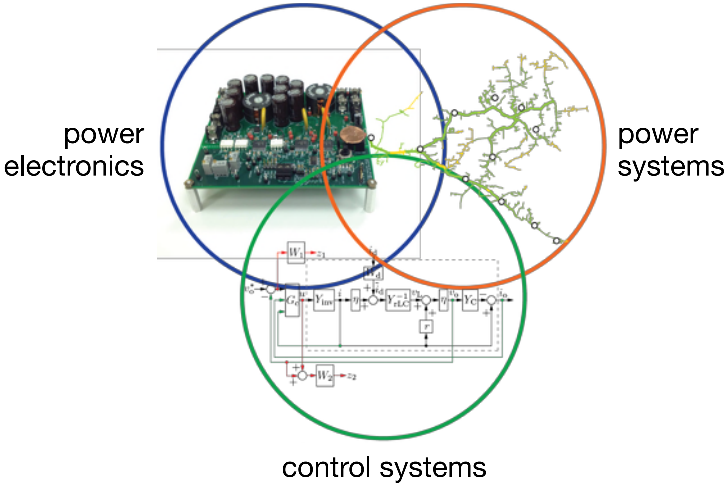
The later sections contain many suggestions for further work, which can be summarized as follows:

- New models are needed which balance the need to include key features without burdening the model (whether for analytical or computational work) with uneven and excessive detail;
- New stability theory which properly reflects the new devices and time-scales associated with CIG, new loads and use of storage;
- Further computational work to achieve sensitivity guidelines including data-based approaches;
- New control methodologies, e.g. new controller to mitigate the high rate of change of frequency in low inertia systems;
- A power converter is a fully actuated, modular, and very fast control system, which are nearly antipodal characteristics to those of a synchronous machine. Thus, one should critically reflect the control of a converter as a virtual synchronous machine; and
- The lack of inertia in a power system does not need to (and cannot) be fixed by simply "adding inertia back" in the systems.

a key unresolved challenge: control of power converters in low-inertia grids

→ industry & power community willing to explore **green-field approach** (see MIGRATE) with **advanced control** methods & **theoretical certificates**

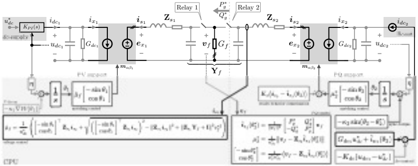
Exciting research domain bridging communities

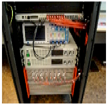


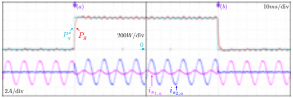
Our research agenda

device-level (power electronics)

- decentralized nonlinear **power converter control** strategies
- experimental **implementation**, validation, & comparison

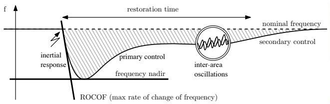


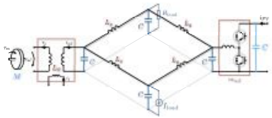


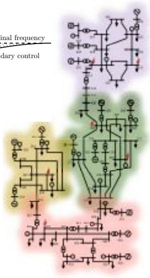


system-level (low-inertia grid)

- low-inertia power system **models, stability, & performance** metrics
- **optimal allocation** of virtual inertia & fast-frequency response services

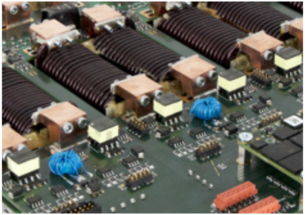


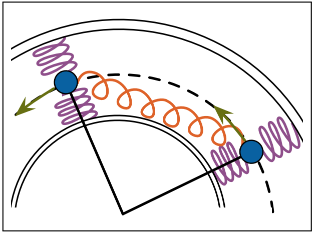


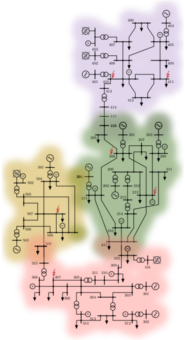


trying to **bridge the gap** from **device-level** to **system level**
& from fundamental control **theory** to practical **experiments**

Focus of today's tutorial







modeling, control specifications, & game changers

- focus: fast time scales & old vs. new
- power system control specifications & limitations

decentralized control of power converters

- grid-forming vs. grid-following: architectures & trade-offs
- grid-forming controls: VSM, droop, matching, & VOC

effect of local controls in large-scale systems

- ancillary service perspective & optimal allocation

All references & many more details in . . .

Foundations and Challenges of Low-Inertia Systems

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Distributed Control and Optimization for Autonomous Power Grids

Florian Dörfler   Saverio Bolognani   John W. Simpson-Porco   Sergio Grammatico

Abstract—**The electric power system is currently undergoing a period of unprecedented changes. Environmental and sustainability concerns lead to replacement of a significant share of conventional fossil fuel-based power plants with renewable energy sources. As a result of this energy transition, centralized bulk generation based on fossil fuel and interfaced with synchronous machines is substituted by distributed**

participation in general provide huge challenges as well as unprecedented opportunities to integrate an end-to-end automated and sustainable socio-technical system.

Parallel to these technological advances, the control, optimization, communication, computer science, and signal processing communities have developed novel methodological

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M11 – STOCKHOLM 13/04/2020-17/04/2020	*Control and Optimization of Autonomous Power Systems*	Florian Dörfler & Saverio Bolognani, *Swiss Federal Institute of Technology (ETHZ), Switzerland*

modeling,

control specifications,

& game changers

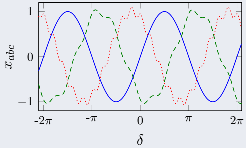
Modeling: signal space in 3-phase AC

three-phase AC

$$\begin{bmatrix} x_a(t) \\ x_b(t) \\ x_c(t) \end{bmatrix} = \begin{bmatrix} x_a(t+T) \\ x_b(t+T) \\ x_c(t+T) \end{bmatrix}$$

periodic with 0 average

$$\frac{1}{T}\int_0^T x_i(t)dt = 0$$

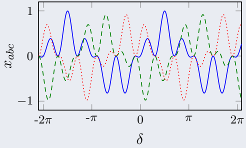


balanced (nearly true)

$$= A(t) \begin{bmatrix} \sin(\delta(t)) \\ \sin(\delta(t) - \frac{2\pi}{3}) \\ \sin(\delta(t) + \frac{2\pi}{3}) \end{bmatrix}$$

so that

$$x_a(t) + x_b(t) + x_c(t) = 0$$

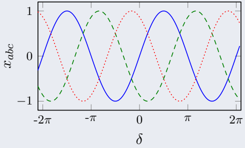


synchronous (desired)

$$= A \begin{bmatrix} \sin(\delta_0 + \omega_0 t) \\ \sin(\delta_0 + \omega_0 t - \frac{2\pi}{3}) \\ \sin(\delta_0 + \omega_0 t + \frac{2\pi}{3}) \end{bmatrix}$$

const. freq & amp

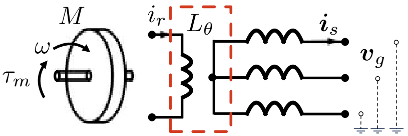
$\Rightarrow$ const. in rot. frame



assumption: balanced $\Rightarrow$ 2d-coordinates $x(t) = [x_\alpha(t)\; x_\beta(t)]$ or $x(t) = A(t)e^{i\delta(t)}$

from currents/voltages to powers: active $p = v^\top i$ and reactive $q = v^T \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} i$

Modeling: synchronous generator



$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = \omega$$

$$M\frac{\mathrm{d}\omega}{\mathrm{d}t} = -D\omega + \tau_m + L_\mathrm{m} i_r \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix}^\top \boldsymbol{i}_s$$

$$L_\mathrm{s}\frac{\mathrm{d}\boldsymbol{i}_s}{\mathrm{d}t} = -R_s\boldsymbol{i}_s + \boldsymbol{v}_g - L_\mathrm{m} i_r \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix}\omega$$

1. **primary energy supply** τ_m from turbine converting thermal to mechanical energy (neglected)

2. mechanical (θ, ω) **swing dynamics** of rotor (flywheel) with inertia M

3. **electro-mechanical energy conversion** through rotating magnetic field with inductance matrix

$$L_\theta = \begin{bmatrix} L_\mathrm{s} & 0 & L_\mathrm{m}\cos\theta \\ 0 & L_\mathrm{s} & L_\mathrm{m}\sin\theta \\ L_\mathrm{m}\cos\theta & L_\mathrm{m}\sin\theta & L_\mathrm{r} \end{bmatrix}$$

(neglected i_r rotor current dynamics)

4. $\boldsymbol{i}_s$ **stator flux dynamics** (sometimes including additional damper windings)

5. connection to grid with voltage $\boldsymbol{v}_g$

Modeling: voltage source converter

1. **primary energy supply** i_{dc} from upstream DC boost converter or storage (neglected)

2. v_{dc} **DC charge dynamics** with capacitance C_{dc}

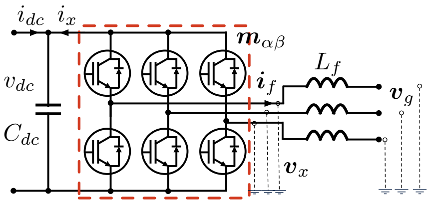
3. **power electronics modulation**

$$i_x = -\boldsymbol{m}^\top \boldsymbol{i}_f \quad \text{and} \quad \boldsymbol{v}_x = \boldsymbol{m} v_{\text{dc}} \,,$$

   with averaged & normalized duty cycle ratios $\boldsymbol{m} \in [-\frac{1}{2}, \frac{1}{2}] \times [-\frac{1}{2}, \frac{1}{2}]$

4. $\boldsymbol{i}_f$ **AC filter dynamics** (sometimes also LC or LCL filter)

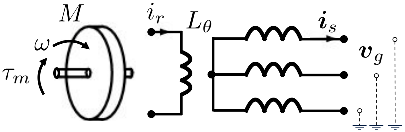
5. connection to grid with voltage $\boldsymbol{v}_g$

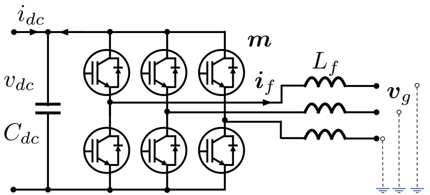


$$C_{\text{dc}} \frac{\mathrm{d}v_{\text{dc}}}{\mathrm{d}t} = -G_{\text{dc}} v_{\text{dc}} + i_{\text{dc}} + \boldsymbol{m}^\top \boldsymbol{i}_f$$

$$L_f \frac{\mathrm{d}\boldsymbol{i}_f}{\mathrm{d}t} = -R_f \boldsymbol{i}_f + \boldsymbol{v}_g - \boldsymbol{m}\, v_{\text{dc}}$$

Comparison: conversion mechanisms





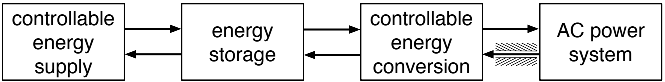
$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = \omega$$

$$M\frac{\mathrm{d}\omega}{\mathrm{d}t} = -D\omega + \tau_m + L_{\mathrm{m}} i_r \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix}^{\top} \boldsymbol{i}_s$$

$$L_{\mathrm{s}}\frac{\mathrm{d}\boldsymbol{i}_s}{\mathrm{d}t} = -R_s \boldsymbol{i}_s + \boldsymbol{v}_g - L_{\mathrm{m}} i_r \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix} \omega$$

$$C_{\mathrm{dc}}\frac{\mathrm{d}v_{\mathrm{dc}}}{\mathrm{d}t} = -G_{\mathrm{dc}} v_{\mathrm{dc}} + i_{\mathrm{dc}} + \boldsymbol{m}^{\top} \boldsymbol{i}_f$$

$$L_f\frac{\mathrm{d}\boldsymbol{i}_f}{\mathrm{d}t} = -R_f \boldsymbol{i}_f + \boldsymbol{v}_g - \boldsymbol{m}\, v_{\mathrm{dc}}$$

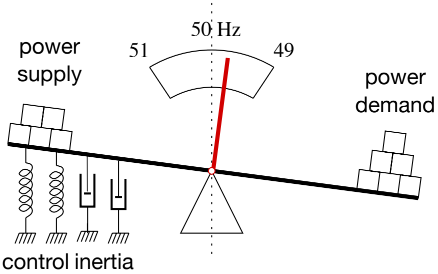


τ_m (slow) vs. i_{dc} (fast)	M (large) vs. C_{dc} (small)	L_θ (physical) vs. $\boldsymbol{m}$ (control)	resilient vs. fragile (over-currents)

physical & robust
vs.
controlled & agile

signal/energy transformer

Deceiving similarities & control limitations



power balances (neglecting small storage elements & losses):

$$\underbrace{\frac{d}{dt}\,\frac{1}{2}\omega^\top M\omega}_{\text{internal energy}} = \underbrace{\omega^\top\tau_m}_{\text{supply}} - \underbrace{\boldsymbol{i}_s^\top\boldsymbol{v}_g}_{\text{demand}} + \underbrace{0}_{\text{conversion}}$$

$$\overbrace{\frac{d}{dt}\,\frac{1}{2}v_{\text{dc}}^\top C_{\text{dc}}v_{\text{dc}}} = \overbrace{i_{\text{dc}}^\top v_{\text{dc}}} - \overbrace{\boldsymbol{i}_s^\top\boldsymbol{v}_g} + \overbrace{0}$$

Antipodal control characteristics

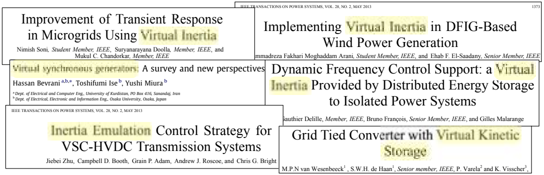
- large M vs. negligible C_{dc} **energy storage** for disturbance rejection
- slow τ_m vs. fast i_{dc} **actuation of the energy supply** (though i_{dc} constrained)
- limited vs. full **actuation of the energy conversion** via L_θ & modulation $\boldsymbol{m}$
- **state constraints**: tolerance to large vs. no over-currents

robust vs. agile
resilient vs. fragile
slow vs. fast actuation
physical vs. control system

Preview: pitfalls of naive inertia emulation

(naive) **baseline solution**:
inverter + storage + control
→ emulate **virtual inertia**

…can & has been done **but**
recall **antipodal characteristics**


Improvement of Transient Response in Microgrids Using Virtual Inertia
Nimish Soni, Student Member, IEEE, Suryanarayana Doolla, Member, IEEE, and Mukul C. Chandorkar, Member, IEEE

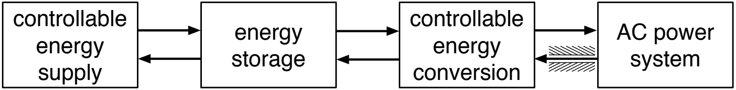
IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 28, NO. 2, MAY 2013 1373
Implementing Virtual Inertia in DFIG-Based Wind Power Generation
…mmadreza Fakhari Moghaddam Arani, Student Member, IEEE, and Ehab F. El-Saadany, Senior Member, IEEE

Virtual synchronous generators: A survey and new perspectives
Hassan Bevrani [a,b,*], Toshifumi Ise [b], Yushi Miura [b]
[a] Dept. of Electrical and Computer Eng., University of Kurdistan, PO Box 416, Sanandaj, Iran
[b] Dept. of Electrical, Electronic and Information Eng., Osaka University, Osaka, Japan

Dynamic Frequency Control Support: a Virtual Inertia Provided by Distributed Energy Storage to Isolated Power Systems
…authier Delille, Member, IEEE, Bruno François, Senior Member, IEEE, and Gilles Malarange

IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 28, NO. 2, MAY 2013
Inertia Emulation Control Strategy for VSC-HVDC Transmission Systems
Jiebei Zhu, Campbell D. Booth, Grain P. Adam, Andrew J. Roscoe, and Chris G. Bright

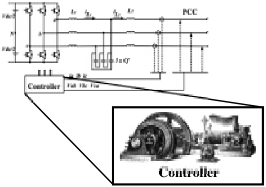
Grid Tied Converter with Virtual Kinetic Storage
M.P.N van Wesenbeeck[1], S.W.H. de Haan[1], Senior member, IEEE, P. Varela[2] and K. Visscher[3],



slow vs. fast | large vs. small | physics vs. control | resilient vs. fragile

telecom analogy (E. Mallada)

- works (under business-as-usual operation)
- there are better solutions (espec. for contingencies)



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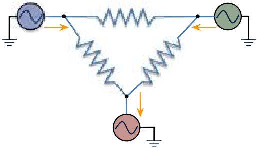
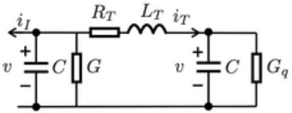
Modeling: the network



interconnecting lines via Π-models & **ODEs**



- **conventional assumption:** quasi-steady state **algebraic model**

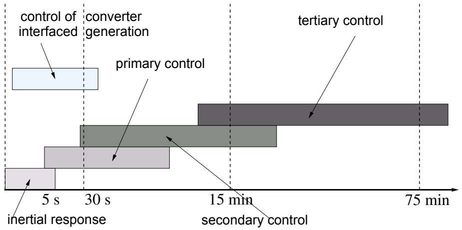
$$\underbrace{\begin{bmatrix} i_1 \\ \vdots \\ i_n \end{bmatrix}}_{\text{nodal injections}} = \underbrace{\begin{bmatrix} \vdots & \ddots & \vdots & \iddots & \vdots \\ -y_{k1} & \cdots & \sum_{j=1}^{n} y_{kj} & \cdots & -y_{kn} \\ \vdots & \iddots & \vdots & \ddots & \vdots \end{bmatrix}}_{\text{Laplacian matrix with } y_{kj} = 1 / \text{ complex impedance}} \underbrace{\begin{bmatrix} v_1 \\ \vdots \\ v_n \end{bmatrix}}_{\text{nodal potentials}}$$

- salient feature: **local** measurement reveals **synchronizing** coupling

$$\underbrace{i_k}_{\text{local variable}} = \underbrace{\sum_j y_{kj} (v_k - v_j)}_{\text{global sync}}$$

- but quasi-steady-state **assumption is flawed** in low-inertia systems

Control specifications

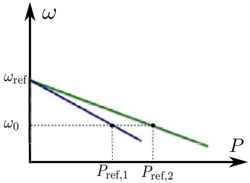


- **nominal synchronous operation**:
  - constant DC states: $\dot{\omega} = \dot{v}_{\mathrm{dc}} = 0$
  - synchronous AC states at ω_{ref}:
    $\dot{\theta} = \omega_{\mathrm{ref}}, \; \frac{\mathrm{d}}{\mathrm{d}t} \boldsymbol{i}_s = \begin{bmatrix} 0 & \omega_{\mathrm{ref}} \\ -\omega_{\mathrm{ref}} & 0 \end{bmatrix} \boldsymbol{i}_s, \ldots$
  - set-points: $\|\boldsymbol{v}_g\| = \boldsymbol{v}_{\mathrm{ref}}$,
    $P \triangleq \boldsymbol{i}_s^\top \boldsymbol{v}_g = P_{\mathrm{ref}}$,
    $Q \triangleq \boldsymbol{i}_s^\top \left[\begin{smallmatrix} 0 & -1 \\ 1 & 0 \end{smallmatrix}\right] \boldsymbol{v}_g = Q_{\mathrm{ref}}$

- **transient disturbance rejection & stabilization:** passively via physics (inertia) & actively via control

- **perturbed synchronous operation** at $\omega \neq \omega_{\mathrm{ref}}$ & power: deviations with specified sensitivities $\partial P / \partial \omega$ (similar for $\boldsymbol{v}$)

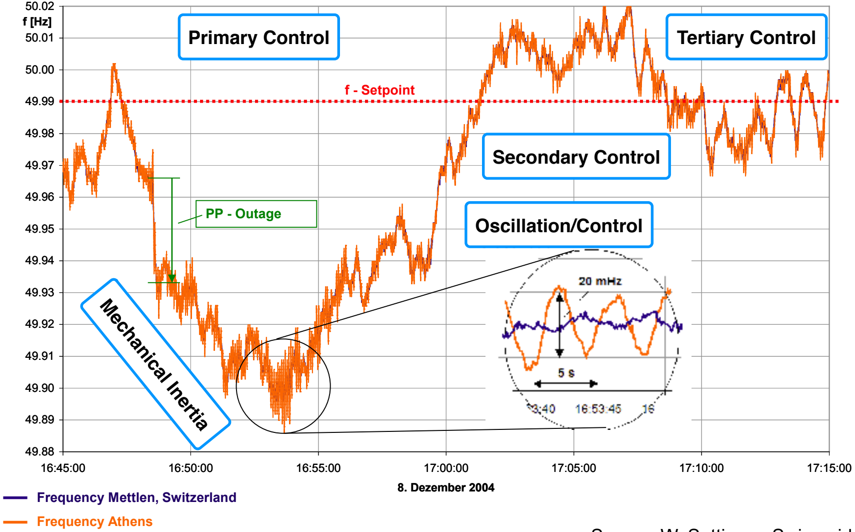
→ decentralized **droop/primary control** $P - P_{\mathrm{ref}} \propto \omega - \omega_{\mathrm{ref}}$



- **secondary control:** regulation of $\omega \to \omega_{\mathrm{ref}}$ (similar for $\boldsymbol{v}$)
- **tertiary control:** (re)scheduling of set-points

} covered in other tutorials

Controllers in action

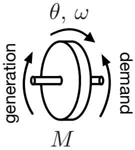


Source: W. Sattinger, Swissgrid

thought experiment:
extrapolation to
low-inertia systems

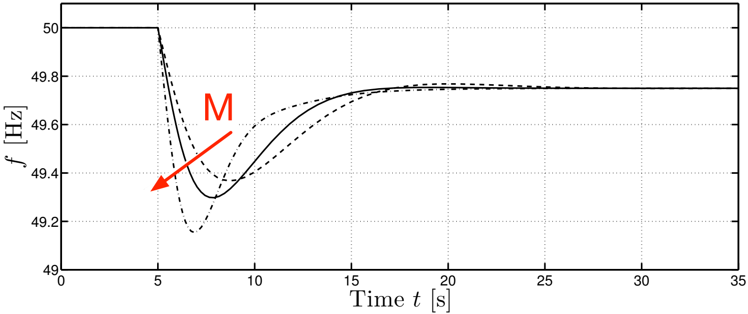
Insight: loss of inertia & frequency stability

We loose our giant electromechanical low-pass filter:

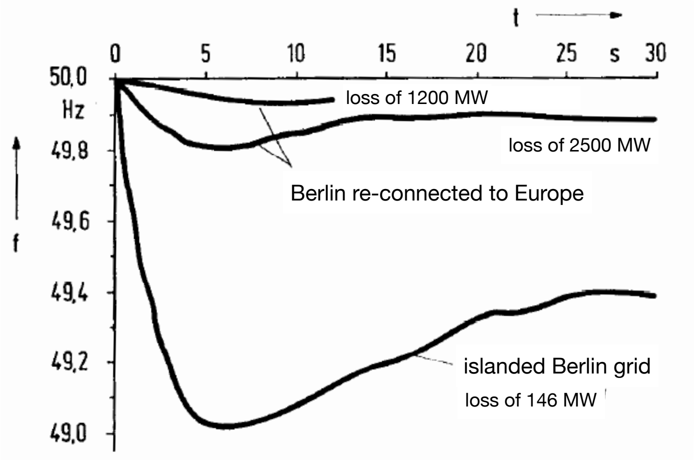


$$\boldsymbol{M}\,\frac{d}{dt}\,\omega(t) \;=\; P_{\text{generation}}(t) - P_{\text{demand}}(t)$$

change of kinetic energy = instantaneous power balance



Berlin post-fault curves: before and after



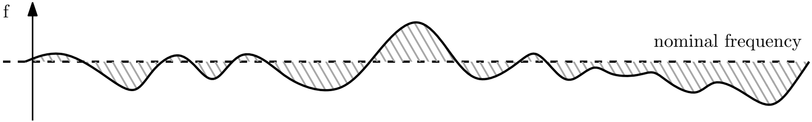
Source: *Energie-Museum Berlin*

This may be true up to first order . . . **but**

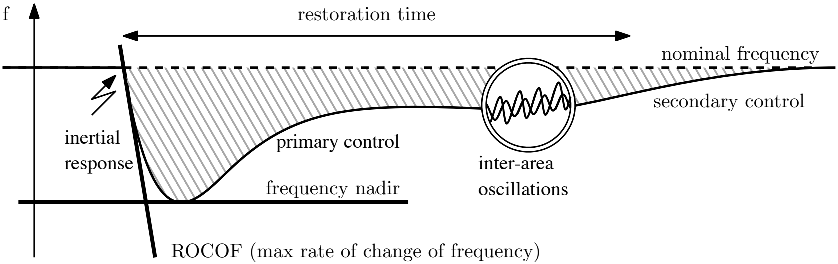
- the **physics** of a low-inertia system are not any longer dominated by mechanical swing dynamics of synchronous machines
- not just loosing inertia but also tight **control** of frequency & voltage
- distributed generation will lead to different **contingencies**
- no more **separation** of (P, ω) and $(Q, \|v\|)$ dynamics / control
- many **new phenomena** : line dynamics, subsychronous oscillations, . . .

→ certainly more **brittle** behavior (faster time scales)

→ for really low inertia levels **anything** can happen

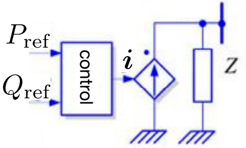
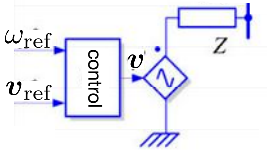


In the long run: free yourself from thinking about power system stability / control as in the conventional text book picture



decentralized control
of power converters

Grid-forming & following converter control

	grid-following	**grid-forming**
converter-type (loose but very common definition)	current-controlled & frequency-following 	voltage-controlled & frequency-forming 
measurement	$(\omega, \lVert\boldsymbol{v}\rVert)$	(P, Q)
set-point	(P, Q)	$(\omega, \lVert\boldsymbol{v}\rVert)$
dynamic reachability	needs a stiff grid to track frequency	can operate in islanded mode & black-start grid

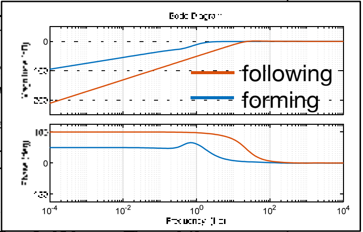
…**feedforward-controlled** (constant) power and voltage sources are forming & following $\rightarrow$ for many reasons **feedback control** is preferable

Remark: definitions are debated

- put 20 experts in a room … $\to$ no universal definition & many hybrid concepts
- many services can be provided both in grid-forming / -following mode
- previous definitions are **compromise** found in MIGRATE project, but we also came up with frequency-domain characterizations "sensitivity to grid frequency"

Characterization of the Grid-forming function of a power source based on its external frequency smoothing capab

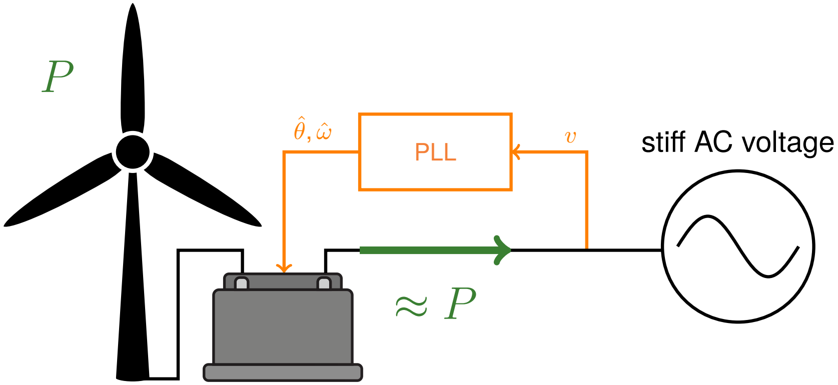
Debry Marie-Sophie, Denis Guillaume, P
Réseau de Transport d'Electricité (Research and De
La Défense
marie-sophie.debry / guillaume.denis / thibault.pre



$\mathcal{H}_\infty$-Control of Grid-Connected
Objectives and Decentralized Stability Certificates

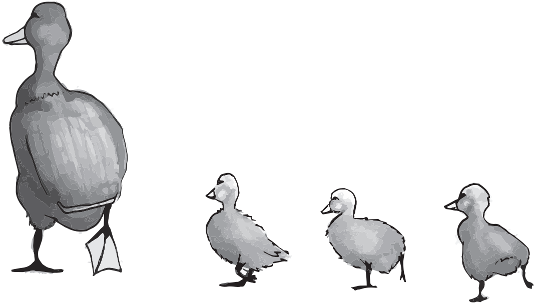
Linbin Huang, Huanhai Xin, and Florian Dörfler

Limitations of grid-following control

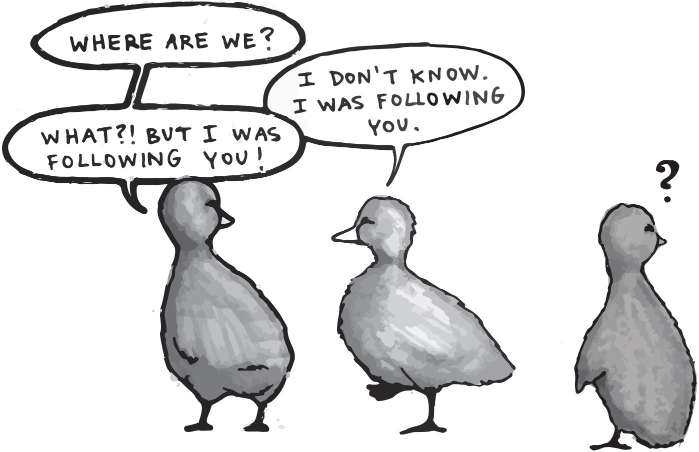


- **is good for** transferring power to a strong grid (main underlying assumption)
- **is not good for** providing a voltage reference, stabilization, or black start
- prevalent today, but **tomorrow's grid** needs (many) grid-forming sources

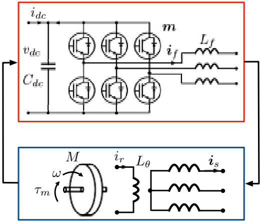
A stiff grid with grid-following sources . . .



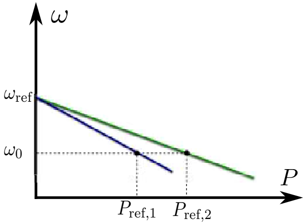
If everyone follows...



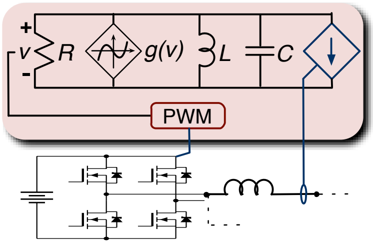
Overview of grid-forming control strategies



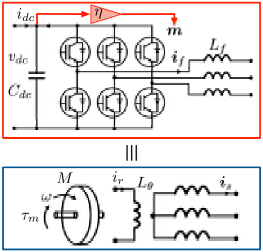
virtual synchronous machine



droop control

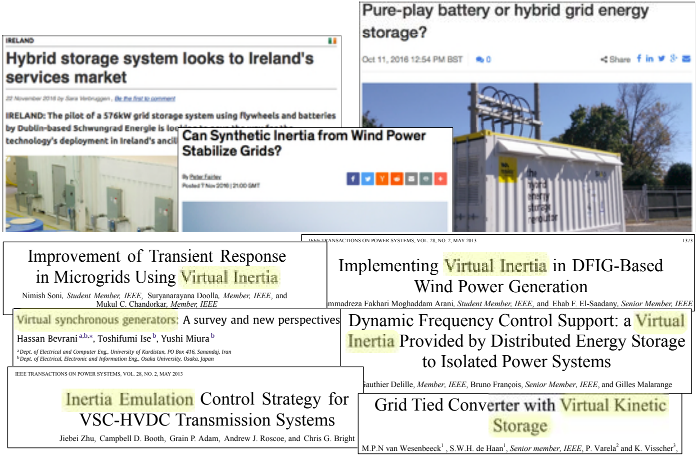


virtual oscillator control (VOC)



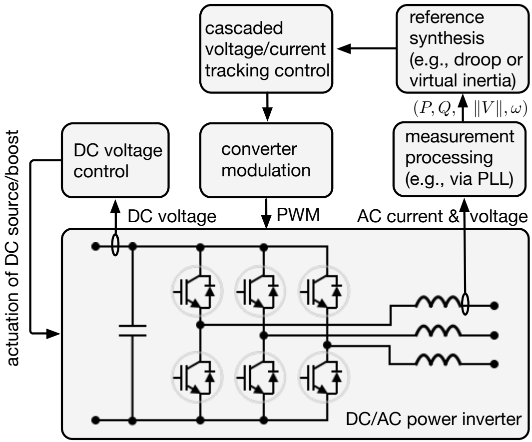
$v_{\rm dc} \sim \omega$ matching control

Naive baseline: virtual inertia emulation



- **PD control** on $\omega(t)$: $\boldsymbol{M}\,\frac{d}{dt}\,\omega(t) + \boldsymbol{D}\,(\omega(t) - \omega_0) \;=\; P_{\text{generation}}(t) - P_{\text{demand}}(t)$
- there are **smarter implementations** at the cost of algorithmic complexity

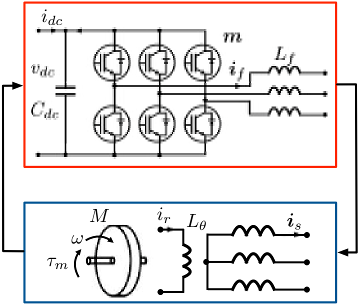
Standard approach to converter control

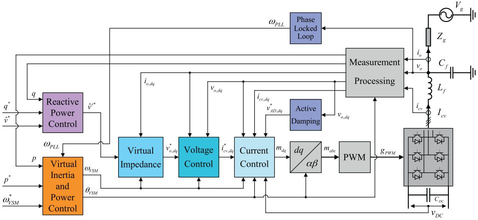


1. acquiring & processing of **AC measurements**
2. synthesis of **references** (voltage/current/power)

   "how would a synchronous generator respond now ?"
3. cascaded PI controllers to **track** references
4. **actuation** via modulation
5. **hidden assumption:** DC-side supply can **instantaneously** provide **unlimited power**

Virtual synchronous machine emulation





D'Arco et al., Electric Power Systems Research, 2015

- **reference**: detailed model of synchronous generator + controls
- **implementation**: low-pass filters for dissipation, virtual impedances for saturation, limiters,. . . tricks

→ most commonly **accepted solution** in **industry** (backward compatibility)

→ **over-parametrized** & ignores **DC source dynamics** and **limits**

→ **poor fit** for converter:

- converter: **fast** actuation & **no** significant **energy storage**
- machine: **slow** actuation & significant **energy storage**

→ **performs poorly** post-fault

→ stability **analysis** is **hopeless**

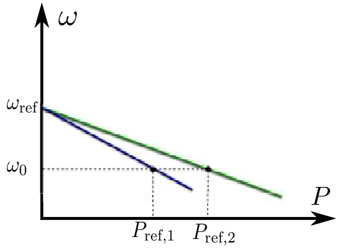
Droop as simplest reference model

- **frequency control** by mimicking $P - \omega$ droop property of synchronous machine:

$$D\left(\omega - \omega_{\text{ref}}\right) \; = \; P - P_{\text{ref}}$$

- **voltage control** via $Q - \|\boldsymbol{v}\|$ droop:

$$\frac{d}{dt}\|v\| = -c_1(\|\boldsymbol{v}\| - v_{\text{ref}}) - c_2(Q - Q_{\text{ref}})$$

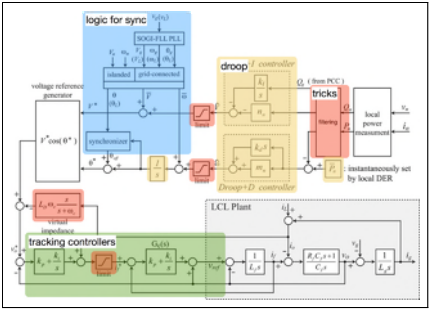


→ **reference** are generator controls

→ direct control of (P, ω) and $(Q, \|\boldsymbol{v}\|)$ **assuming they are independent** (approx. true only near steady state)

→ ignores DC **source dynamics**

→ requires **tricks in implementation** similar to virtual synchronous machine

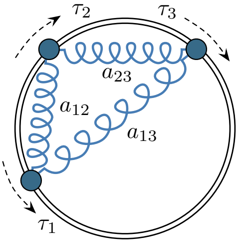


Droop control is *de facto* baseline solution

- after (lots of) deliberate tuning, it **works well locally** near steady state
- admits both **grid-forming & grid-following** implementations
- simplified droop models are amenable to theoretic **analysis & certificates**

(simplified) **frequency droop** = coupled oscillators

$$\underbrace{\frac{d}{dt}\theta_i}_{\frac{d}{dt}\text{ terminal voltage}} = \underbrace{\tau_i}_{\text{active power set-point}} \underbrace{- \sum\nolimits_j a_{ij} \sin(\theta_i - \theta_j)}_{\text{active power flows from grid}}$$



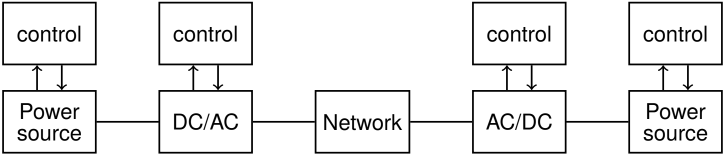
⇒ part of many **grid codes & ancillary service** markets

ø **poor post-fault performance** due to delays, wind-up, decoupling, SISO, …

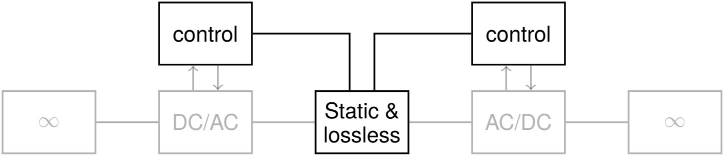
ø **no stability certificates** for detailed, nonlinear, & interconnected systems

ø unclear if droop control is the **long-term solution (?)** for low-inertia systems matching control

Power sources & signal transformers

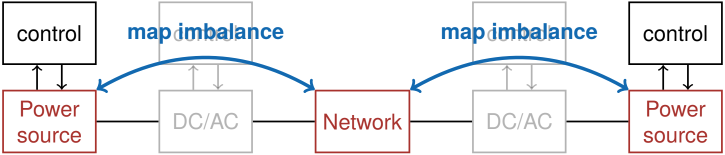


complete system model



abstraction & objectives of previous controllers

Power sources & signal transformers cont'd



power source

- governs **system-level behavior**
- response **time**, **power**, . . .

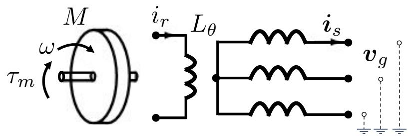
DC/AC converter

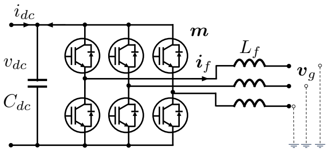
- acts as signal **transformer**
- **negligible** controlled dynamics

Key insights

- DC side & power source cannot be neglected
- focus on main **energy storage** elements & **energy source**
- synchronous machine **maps** power **imbalance** to **turbine** & **governor**
- converter maps imbalance power to . . . ?

Seeking more natural control strategies





$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = \omega$$

$$M\frac{\mathrm{d}\omega}{\mathrm{d}t} = -D\omega + \tau_m + L_\mathrm{m} i_r \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix}^\top \boldsymbol{i}_s$$

$$L_\mathrm{s}\frac{\mathrm{d}\boldsymbol{i}_s}{\mathrm{d}t} = -R_s\boldsymbol{i}_s + \boldsymbol{v}_g - L_\mathrm{m} i_r \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix}\omega$$

$$\frac{\mathrm{d}\delta}{\mathrm{d}t} = \eta\cdot v_\mathrm{dc}$$

$$C_\mathrm{dc}\frac{\mathrm{d}v_\mathrm{dc}}{\mathrm{d}t} = -G_\mathrm{dc}v_\mathrm{dc} + i_\mathrm{dc} + m_\mathrm{ampl}\begin{bmatrix} -\sin\delta \\ \cos\delta \end{bmatrix}^\top \boldsymbol{i}_f$$

$$L_f\frac{\mathrm{d}\boldsymbol{i}_f}{\mathrm{d}t} = -R_f\boldsymbol{i}_f + \boldsymbol{v}_g - m_\mathrm{ampl}\begin{bmatrix} -\sin\delta \\ \cos\delta \end{bmatrix} v_\mathrm{dc}$$

1. modulation in polar coordinates:

$$\boldsymbol{m} = m_\mathrm{ampl}\begin{bmatrix} -\sin\delta \\ \cos\delta \end{bmatrix} \quad \& \quad \dot{\delta} = m_\mathrm{freq}$$

2. matching: $m_\mathrm{freq} = \eta v_\mathrm{dc}$ with $\eta = \frac{\omega_\mathrm{ref}}{v_\mathrm{dc,ref}}$

→ duality: $C_\mathrm{dc} \sim M$ is equivalent inertia

structural similarities (duality):

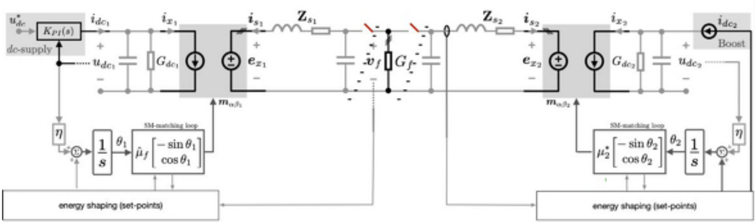
- states: $\theta = \delta$, $\omega = \eta v_\mathrm{dc}$, $\boldsymbol{i}_s = \boldsymbol{i}_f$
- control: $u_\mathrm{ampl} = L_m i_r$, $i_\mathrm{dc}/\eta = \tau_m$

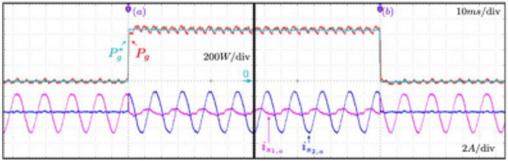
→ equivalent inertia: $M \equiv C_\mathrm{dc}/\eta^2$ & energy imbalance signal $\omega \equiv v_{dc}$

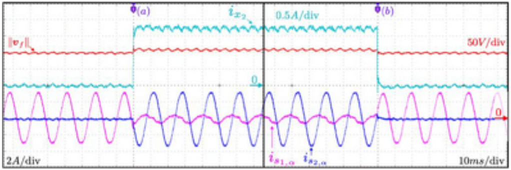
Properties of matching control

- simple & robust **implementation**: $v_{\text{dc}} \longrightarrow \boxed{\frac{\eta}{s}} \xrightarrow{\delta} \boxed{m_{\text{ampl}} \begin{bmatrix} -\sin\delta \\ \cos\delta \end{bmatrix}} \longrightarrow \boldsymbol{m}$
- exploits **structural similarities** & DC/AC **energy imbalance**
  - clarifies impact of DC side dynamics & limitations
  - similar results for higher-order machine models
  - saturating DC current $\rightarrow$ saturating AC current (no need for virtual impedance etc.)
- can also be derived from **principled nonlinear control**
  - virtual angle + matching $=$ internal model + passive interconnection (IDA-PBC)
- **energy shaping** via i_{dc} & u_{mag} to achieve further control objectives
  - damping/droop assignment (stability)
  - tracking set-points (PQ or PV)
  - add virtual capacitance (inertia)
- closed-loop **certificates**: incremental stability & passivity $\approx$ energy decreasing
- closed loop is **only structurally equivalent** to synchronous machine
  $\rightarrow$ time constants need to be tuned differently (later: $\mathcal{H}_2$-optimal tuning)

Rapid prototyping experimental validation



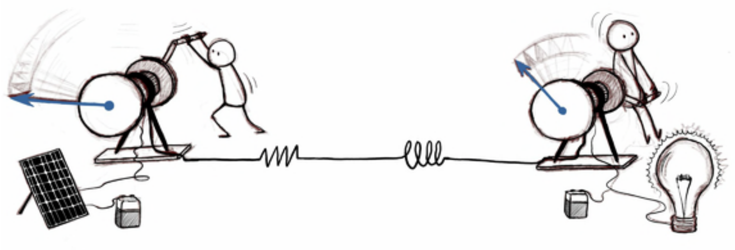




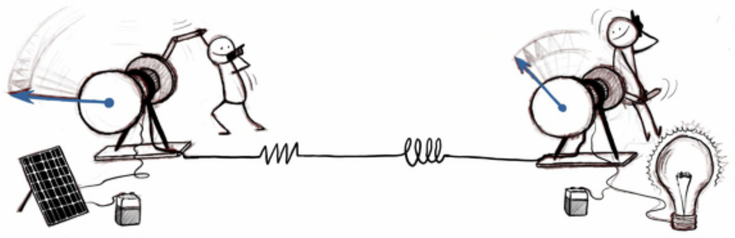
virtual oscillator control (VOC)

Cartoon summary of VOC approach

Conceptually, inverters are oscillators that have to synchronize

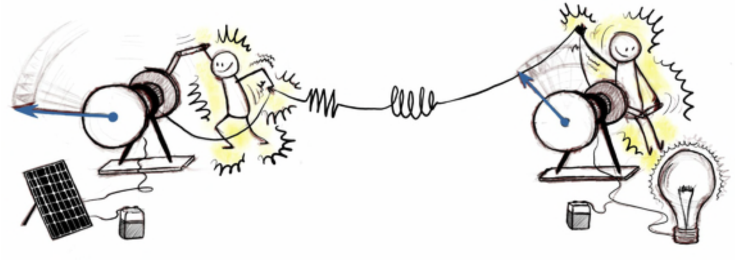


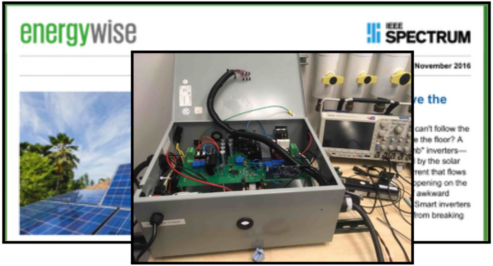
Hypothetically, they could sync by communication (not feasible)



Cartoon summary of VOC approach

Colorful idea: inverters sync through physics & clever local control





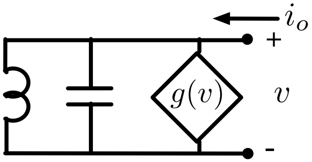
theory: sync of coupled oscillators & nonlinear decentralized control

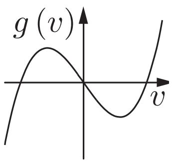
power systems/electronics **experiments** @NREL outstanding performance (superior to droop control)

Original **V**irtual **O**scillator **C**ontrol (VOC)

nonlinear & open limit cycle oscillator as reference model for terminal voltage (1-phase):

$$\ddot{v} + \omega_0^2 v + g(v) = i_o$$



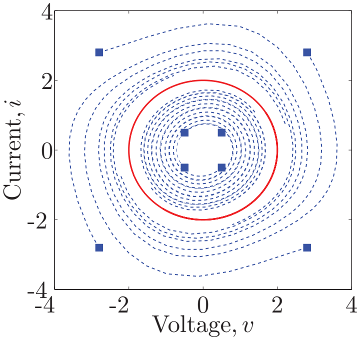


- simplified model amenable to theoretic analysis

→ **almost global synchronization** & **local droop**

- in practice proven to be **robust mechanism** with performance superior to droop & others

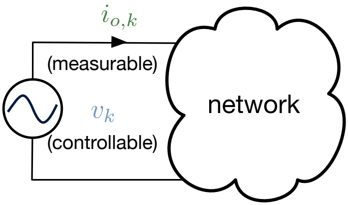
→ **problem**: cannot be controlled(?) to meet specifications on amplitude & power injections



[J. Aracil & F. Gordillo, '02], [Torres, Hespanha, Moehlis, '11],
[Johnson, Dhople, Krein, '13], [Dhople, Johnson, Dörfler, '14]

improvement of original ad hoc
virtual oscillator control (VOC)

Model & control objectives (assumptions easy to generalize)



Simplified multi-converter system model

- converter $=$ **terminal voltage** $v_k \in \mathbb{R}^2$
- **line dynamics** = steady-state Π-model with line admittance $\|Y_{jk}\| = 1/\sqrt{r_{kj}^2 + \omega_0^2 \ell_{kj}^2}$
- **homogeneous lines** with $\kappa = \frac{\ell_{jk}}{r_{jk}}$ constant

Desired steady-state behavior

- nominal **synchronous frequency**

$$\frac{d}{dt} v_k = \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix} v_k$$

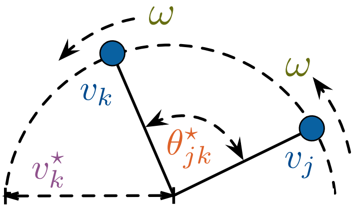
- voltage **amplitude** (uniform for this talk)

$$\|v_k\| = v^\star$$

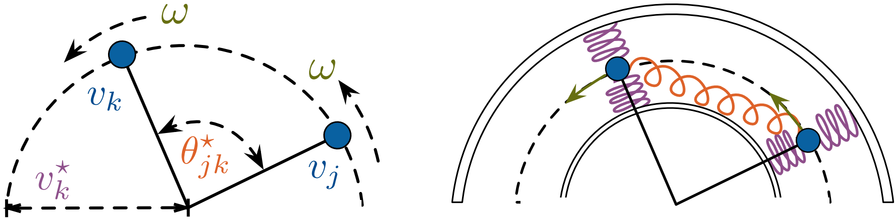
- active & reactive **power injection**

$$v_k^\top i_{o,k} = p_k^\star \quad , \quad v_k^\top \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} i_{o,k} = q_k^\star$$

$\Leftrightarrow$ relative **angles**: $v_k = \begin{bmatrix} \cos(\theta_{jk}^\star) & -\sin(\theta_{jk}^\star) \\ \sin(\theta_{jk}^\star) & \cos(\theta_{jk}^\star) \end{bmatrix} v_k$



Colorful idea: closed-loop target dynamics



$$\frac{d}{dt}\boldsymbol{v_k} = \underbrace{\begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix} \boldsymbol{v_k}}_{\text{rotation at } \omega} + c_1 \cdot \underbrace{\left(\|v_k\|^{\star 2} - \|\boldsymbol{v}_k\|^2 \right) \boldsymbol{v}_k}_{\text{amplitude regulation to } v^\star_k}$$

$$+ \; c_2 \cdot \underbrace{\sum_{j=1}^{n} w_{jk} \left(\boldsymbol{v}_j - \begin{bmatrix} \cos(\theta^\star_{jk}) & -\sin(\theta^\star_{jk}) \\ \sin(\theta^\star_{jk}) & \cos(\theta^\star_{jk}) \end{bmatrix} \boldsymbol{v}_k \right)}_{\text{synchronization to desired relative angles } \theta^\star_{jk}}$$

Decentralized implementation of dynamics

$$\underbrace{\sum_j w_{jk}(v_j - R(\theta^\star_{jk})v_k)}_{\text{need to know } w_{jk},\, v_j,\, v_k \text{ and } \theta^\star_{jk}} = \underbrace{\sum_j w_{jk}(v_j - v_k)}_{\text{“Laplacian” feedback}} + \underbrace{\sum_j w_{jk}(I - R(\theta^\star_{jk}))v_k}_{\text{local feedback: } \mathcal{K}_k(\theta^\star)v_k}$$

insight I: non-local measurements from **communication via physics**

$$\underbrace{i_{o,k}}_{\text{local feedback}} = \underbrace{\sum_j y_{jk}(v_j - v_k)}_{\text{distributed feedback with } w_{jk} = y_{kj} = \|y_{kj}\|\, R(\kappa)^{-1}}$$

insight II: angle set-points & line-parameters from **power flow equations**

$$\left.\begin{aligned} p^\star_k &= v^{\star 2} \sum_j \frac{r_{jk}(1-\cos(\theta^\star_{jk})) - \omega_0 \ell_{jk} \sin(\theta^\star_{jk})}{r^2_{jk} + \omega_0^2 \ell^2_{jk}} \\ q^\star_k &= -v^{\star 2} \sum_j \frac{\omega_0 \ell_{jk}(1-\cos(\theta^\star_{jk})) + r_{jk} \sin(\theta^\star_{jk})}{r^2_{jk} + \omega_0^2 \ell^2_{jk}} \end{aligned}\right\} \Rightarrow \underbrace{\mathcal{K}_k(\theta^\star)}_{\text{global parameters}} = \underbrace{\frac{1}{v^{\star 2}} R(\kappa) \begin{bmatrix} q^\star_k & p^\star_k \\ -p^\star_k & q^\star_k \end{bmatrix}}_{\text{local parameters}}$$

Properties of virtual oscillator control

1. desired target dynamics can be realized via **fully decentralized control**

$$\frac{d}{dt}v_k = \underbrace{\left[\begin{smallmatrix} 0 & -\omega \\ \omega & 0 \end{smallmatrix}\right] v_k}_{\text{rotation at } \omega_0} + \underbrace{c_1 \cdot R(\kappa)\left(\frac{1}{v^{\star 2}}\begin{bmatrix} q_k^\star & p_k^\star \\ -p_k^\star & q_k^\star \end{bmatrix} v_k - i_{o,k}\right)}_{\text{synchronization through physics}} + \underbrace{c_2 \cdot \left(v^{\star 2} - \|v_k\|^2\right) v_k}_{\text{local amplitude regulation}}$$

2. connection to **droop control** revealed in polar coordinates (for inductive grid)

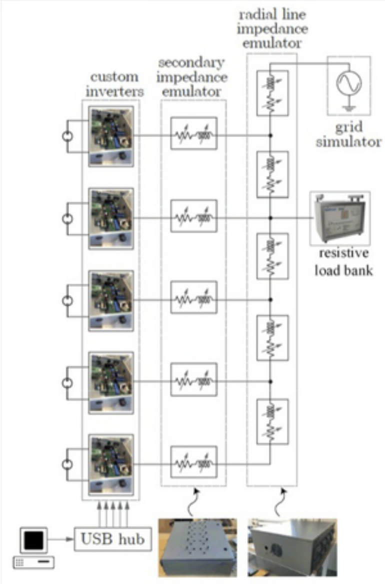
$$\frac{d}{dt}\theta_k = \omega_0 + c_1\left(\frac{p_k^\star}{v^{\star 2}} - \frac{p_k}{\|v_k\|^2}\right) \underset{\|v_k\|\approx 1}{\approx} \omega_0 + c_1\left(p_k^\star - p_k\right) \qquad (p-\omega \text{ droop})$$

$$\frac{d}{dt}\|v_k\| \underset{\|v_k\|\approx 1}{\approx} c_1\left(q_k^\star - q_k\right) + c_2\left(v^\star - \|v_k\|\right) \qquad (q-\|v\| \text{ droop})$$

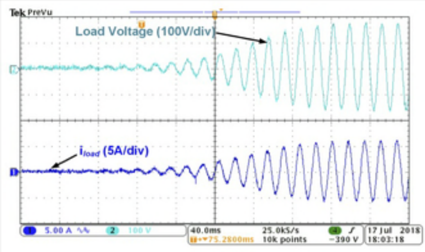
3. **almost global asymptotic stability** if

- **power transfer** "small enough" compared to **network connectivity**
- **amplitude control** slower than **synchronization control**

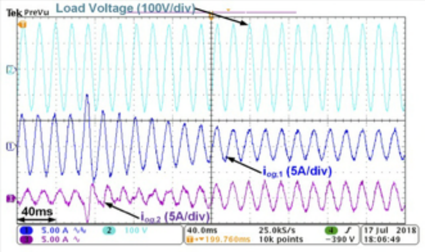
Experimental setup @ NREL



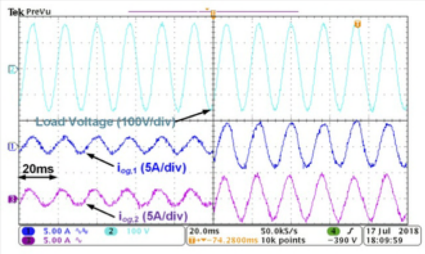
Experimental results



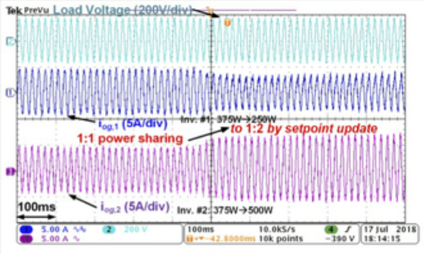
black start of inverter #1 under 500 W load
(making use of almost global stability)



connecting inverter #2 while inverter #1 is
regulating the grid under 500 W load



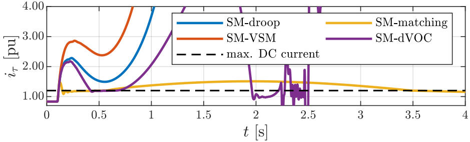
250 W to 750 W load transient with two
inverters active

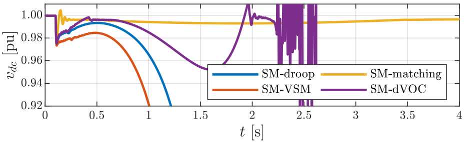


change of setpoint: $p^\star$ of inverter #2
updated from 250 W to 500 W

relative comparison

Comparison of control strategies @AIT





Interactions of Grid-Forming Power Converters and Synchronous Machines – A Comparative Study

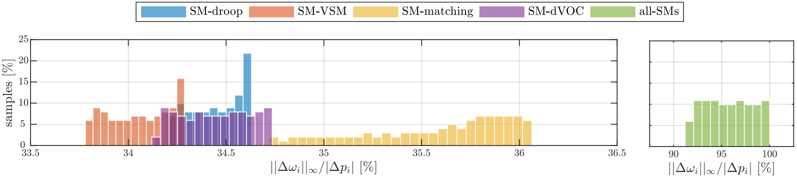
Ali Tayyebi, Dominic Groß, Adolfo Anta, Friederich Kupzog and Florian Dörfler

- **all perform well** nominally & under minor disturbances
- **relative resilience**:

  matching > VOC > droop > virtual synchronous machine

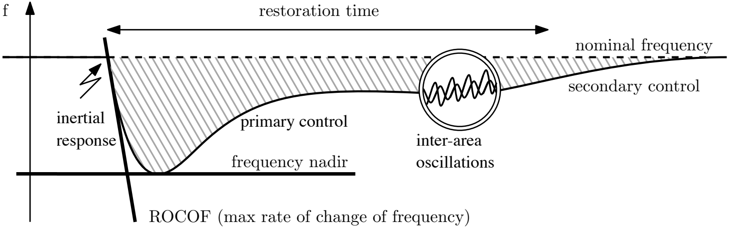
→ it is a very poor strategy for a converter to emulate a flywheel

- promising **hybrid control** directions: VOC + matching



system-level optimization

Performance metrics for power systems



System norm quantifying signal amplifications

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

→ system →

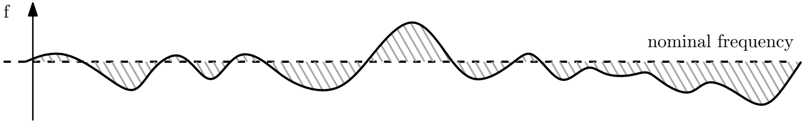
performance outputs: integral, peak, ROCOF, restoration time, ...

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

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



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

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 $\lim_{t\to\infty} \mathbb{E}\left(\mathbf{y}(t)^\mathsf{T}\, \mathbf{y}(t)\right)$

System model & virtual inertia realization

nonlinear DAE dynamics

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

x_s : system & control states

z_s : network signals

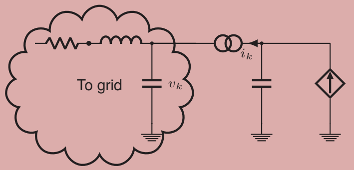
i : current injections/faults

virtual inertia & damping

= fast frequency response implemented by means of

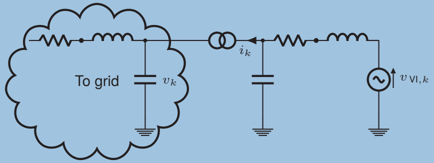
- converters & storage
- 2nd-order droop control

follow the grid: lock to ω



grid-following

form the grid: generate ω

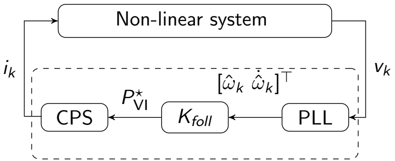


grid-forming

Comparison: virtual inertia implementations

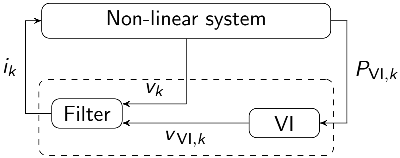
grid-following

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



grid-forming

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



droop via phased-locked loop

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

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

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

grid-forming 2nd-order droop

$$\dot{\theta}_{\text{VI},k} = \omega_{\text{VI},k}$$

$$\dot{\omega}_{\text{VI},k} = -\tilde{d}_k \, \tilde{m}_k^{-1} \omega_{\text{VI},k} - \tilde{m}_k^{-1} P$$

$$\dot{\omega}_{\text{VI},k} = K_{\textit{form},k} \, [\omega_{\text{VI},k} \ \ P]^\top$$

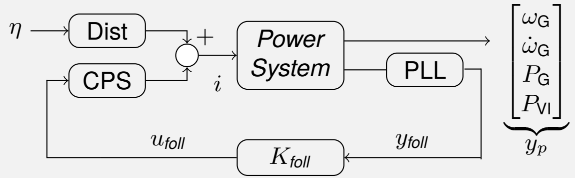
Note: control coefficients interpretable as “virtual inertia & damping” or “P & D”

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, . . .



$$\Delta\dot{x}_{cl} = (A + BKC)\Delta x_{cl} + B_g(\Pi^{1/2})\eta, \;\; \Delta y_p = C_p \Delta x_{cl}$$

linearized closed loop for optimal control design

Optimal control formulation

$$\underset{P,\,K}{\text{minimize}} \quad \|G\|_{\mathcal{H}_2}^2 = \text{trace}(B_g{}^\top P\, B_g) \quad \text{performance metric}$$

$$\text{subject to} \quad K(m,\, d) \in S \quad \text{constraint set}$$

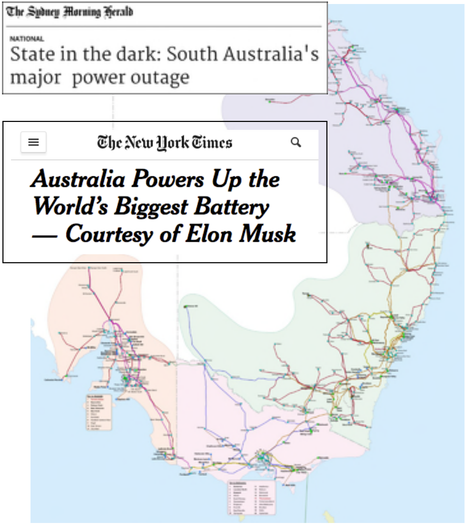
$$P\,(A + BKC) + (A + BKC)^\top P + C_p^\top C_p = \mathbb{O} \quad \text{Lyapunov equation}$$

Key Insights:

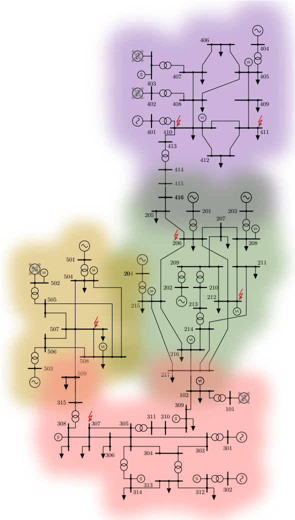
1. **non-convex** problem in P, K
2. **conservative** convex upper/lower bounds can be obtained
3. assume knowledge of **disturbance** profile Π or go for min-max
4. **gradient-based** approach: scalable, can handle constraints, suboptimal
5. **complexity** of gradient computation $\mathcal{O}(n^3)$ via controllability Gramian

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

Case-study: South-East Australian Grid

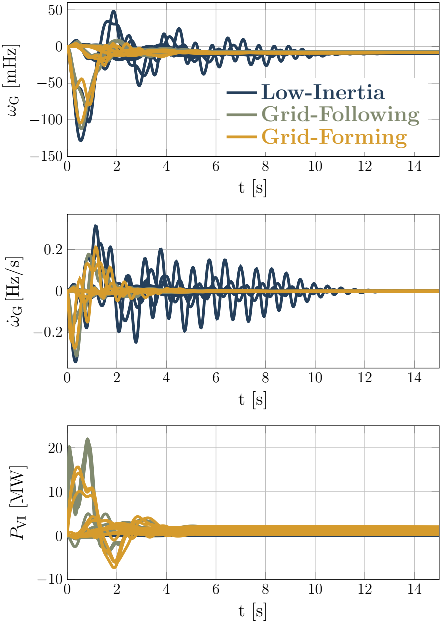


grid topology



simulink model

Closed-loop simulations



Non-linear model

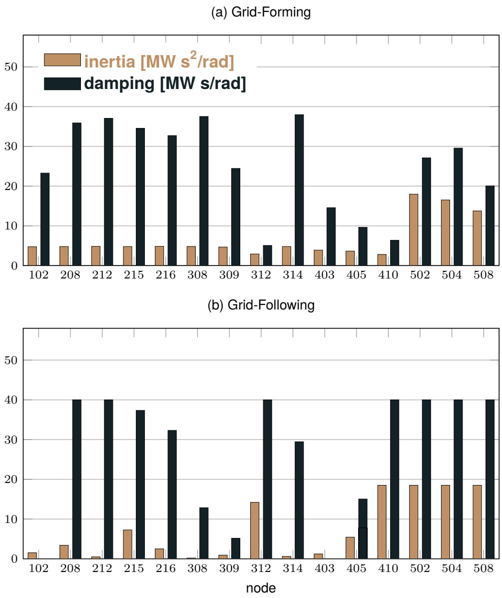
- 54 buses, 14 gens, & **15 converters**
- control: governors, AVRs, & PSSs
- **replace** generators with controllable power sources + virtual inertia
- numerically linearize model, choose performance inputs/outputs & gradient-based optimization routine
- non-linear closed-loop simulations: 200 MW disturbance at node 508

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



Observations

- both control modes allocate virtual inertia in (blackout & battery) **area 5**
- **grid-following** : more reliance on damping (due to PLL-delay in $\dot{\omega}$)
- **grid-forming** : results in a more uniform (thus robust) allocations

  $\rightarrow$ **total inertia/damping** not crucial

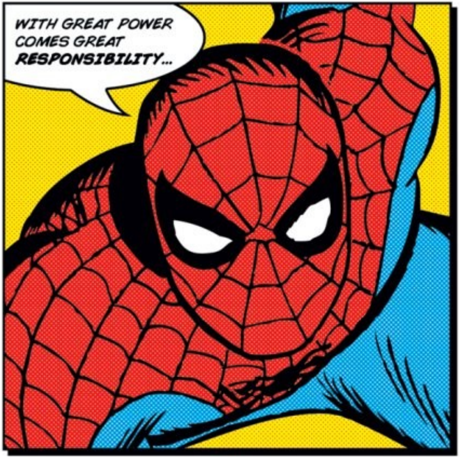
  $\rightarrow$ **spatial allocation** matters a lot

  $\rightarrow$ implications for pricing & markets

Conclusions

- low-inertia stability & converter control are **major bottlenecks** for sustainability
- power system community & industry are open to **green-field** approaches

→ **low-inertia systems — opportunity for collaboration: control & power**




POWER IS NOTHING WITHOUT CONTROL

All references & many more details in . . .

Foundations and Challenges of Low-Inertia Systems

(Invited Paper)

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Distributed Control and Optimization for Autonomous Power Grids

Florian Dörfler   Saverio Bolognani   John W. Simpson-Porco   Sergio Grammatico

***Abstract*— The electric power system is currently undergoing a period of unprecedented changes. Environmental and sustainability concerns lead to replacement of a significant share of conventional fossil fuel-based power plants with renewable energy sources. As a result of this energy transition, centralized bulk generation based on fossil fuel and interfaced with synchronous machines is substituted by distributed**

participation in general provide huge challenges as well as unprecedented opportunities to integrate an end-to-end automated and sustainable socio-technical system.

Parallel to these technological advances, the control, optimization, communication, computer science, and signal processing communities have developed novel methodological

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my collaborators