Distributed control & optimization for autonomous power grids

Tutorial, European Control Conference 2019

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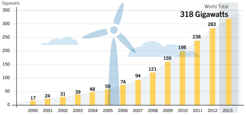
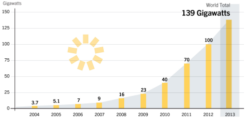
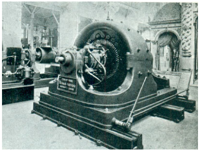
(recent) power systems control challenges

→ integration of renewable sources





→ changing generation technology



opportunities:

- converter-interfaced sources

→ fast / modular / flexible actuation

- technological advances

→ sensing / actuation / communication

- scientific advances

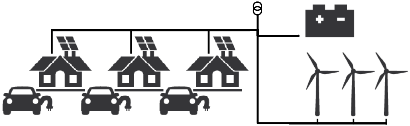
→ control / optimization / learning

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

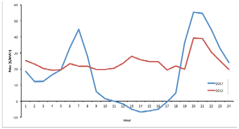
≡ opportunity for **control**

→ scaling

→ distributed generation & prosumption

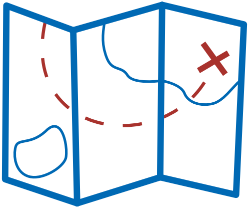


→ liberalized markets




POWER IS NOTHING WITHOUT CONTROL

Selected *autonomous control* topics today



1. **Decentralized Control of Low-Inertia Power Systems**
   Florian Dörfler

2. **Real-Time Control of Distribution Grids**
   Saverio Bolognani

3. **Optimal & Distributed Frequency Control of Transmission Grids**
   John W. Simpson-Porco

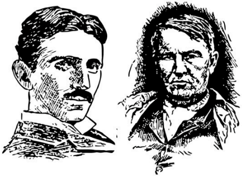
4. **Coordination of Energy Supply & Demand**
   Sergio Grammatico

Decentralized Control of Low-Inertia Power Systems

Florian Dörfler, ETH Zürich

Tutorial, European Control Conference 2019

Replacing the system foundation



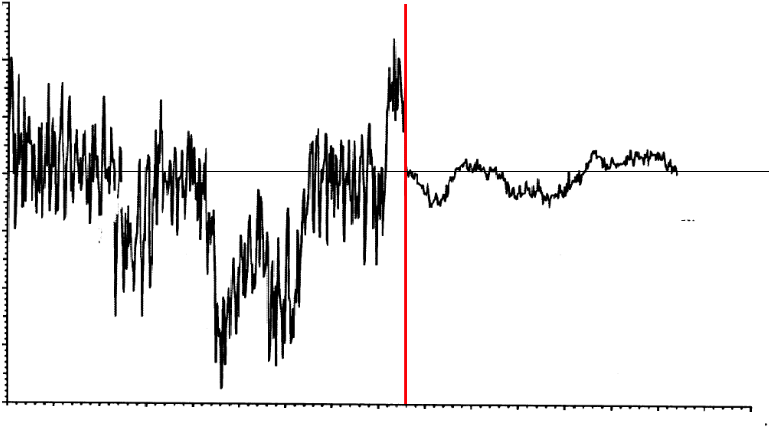
fuel & synchronous machines

- − **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

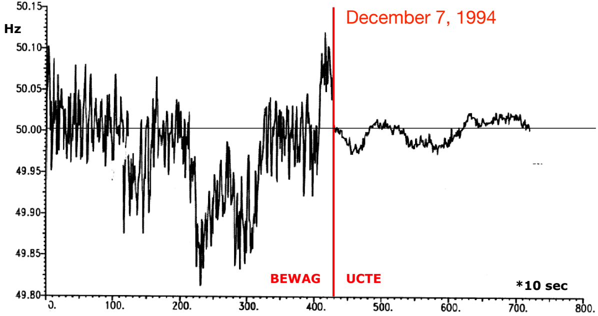
- + **sustainable**
- − **distributed & variable** generation
- − almost **no energy storage**
- − **no** inherent **self-synchronization**
- − **fragile** voltage / frequency **control**
- + **fast / flexible / modular control**

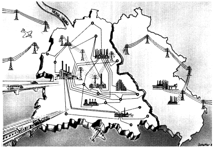
What do we see here ?



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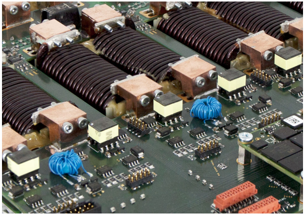
The later sections contain many suggestions for further work, which can be summarized as follows:

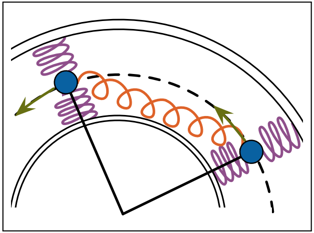
- New models are needed which balance the need to include key features without burdening the model (whether for analytical or computational work) with uneven and excessive detail;
- New stability theory which properly reflects the new devices and time-scales associated with CIG, new loads and use of 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.

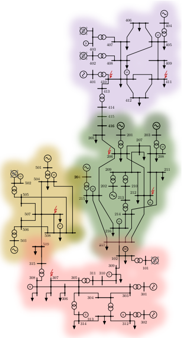
a key unresolved challenge: control of power converters in low-inertia grids
→ industry & power community willing to explore **green-field approach** (see MIGRATE) with **advanced control** methods & **theoretical certificates**

Focus of today's tutorial

all references can be found in the paper







synchronous generators & power converters

- modeling, similarities & differences, & control limitations

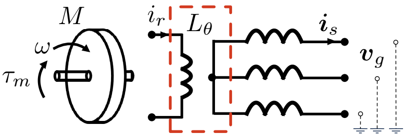
power system control specifications

- focus: decentralized control on fast time scales

decentralized control of power converters

- grid-forming & grid-following specifications
- droop, virtual inertia, virtual oscillator, & matching control

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}

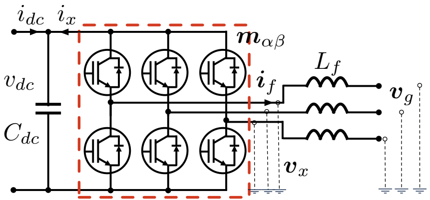
3. **power electronics modulation**

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

   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)

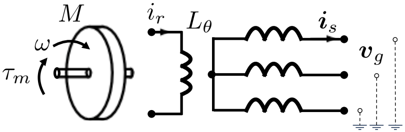
5. connection to grid with voltage $\boldsymbol{v}_g$



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

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

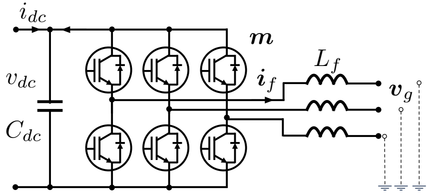
Comparison: conversion mechanisms



$$\frac{d\theta}{dt} = \omega$$

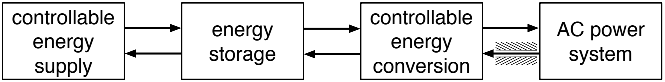
$$M\frac{d\omega}{dt} = -D\omega + \tau_m + L_m i_r \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix}^\top \boldsymbol{i}_s$$

$$L_s\frac{d\boldsymbol{i}_s}{dt} = -R_s\boldsymbol{i}_s + \boldsymbol{v}_g - L_m i_r \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix}\omega$$



$$C_{dc}\frac{dv_{dc}}{dt} = -G_{dc}v_{dc} + i_{dc} + \boldsymbol{m}^\top\boldsymbol{i}_f$$

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

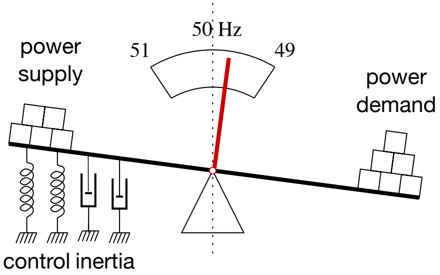


physical & robust
vs.
controlled & agile

signal/energy transformer

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)

Deceiving similarities & control limitations



power balances (neglecting small storage elements & losses):

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

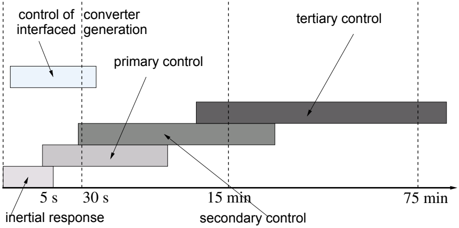
$$\overbrace{\frac{d}{dt}\ \frac{1}{2} v_{\text{dc}}^{\top} C_{\text{dc}} v_{\text{dc}}}^{\text{internal energy}} = \overbrace{i_{\text{dc}}^{\top} v_{\text{dc}}}^{\text{supply}} - \overbrace{\boldsymbol{i}_s^{\top}\boldsymbol{v}_g}^{\text{demand}} + \overbrace{0}^{\text{conversion}}$$

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

Control specifications

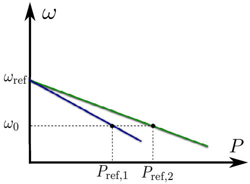


- **nominal synchronous operation**:
  - constant DC states: $\dot{\omega} = \dot{v}_{\mathsf{dc}} = 0$
  - synchronous AC states at ω_{ref}:
    $\dot{\theta} = \omega_{\mathsf{ref}}, \ \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}_s = \begin{bmatrix} 0 & \omega_{\mathsf{ref}} \\ -\omega_{\mathsf{ref}}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

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

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

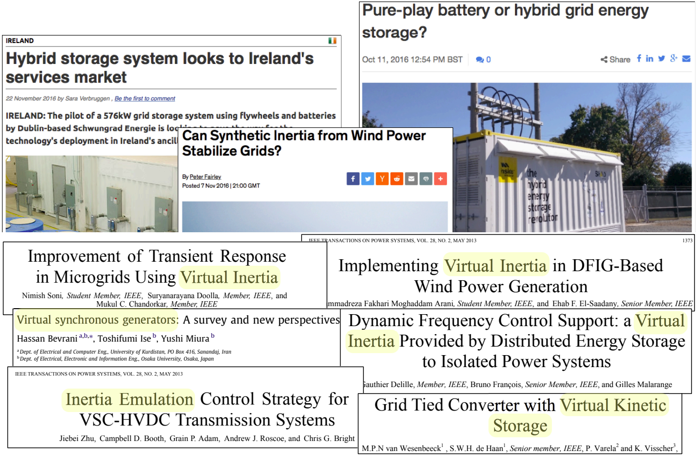
$\rightarrow$ decentralized **droop/primary control** $P - P_{\mathsf{ref}} \propto \omega - \omega_{\mathsf{ref}}$



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

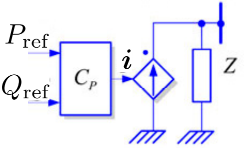
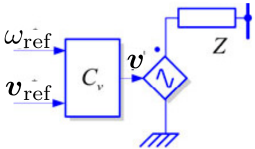
} covered in other tutorials

Baseline: virtual inertia emulation



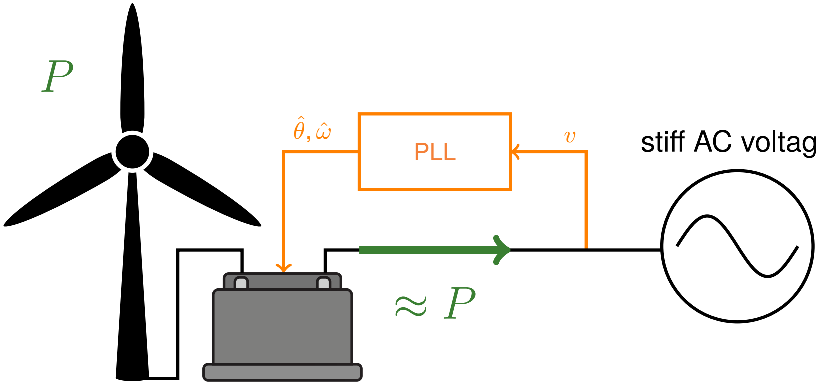
- **PD control** on $\omega(t)$: $\boldsymbol{M}\frac{d}{dt}\omega(t) + \boldsymbol{D}(\omega(t) - \omega_0) = P_{\text{generation}}(t) - P_{\text{demand}}(t)$
- there are **smarter implementations** at the cost of algorithmic complexity

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	$(\omega, \|\boldsymbol{v}\|)$	(P, Q)
set-point	(P, Q)	$(\omega, \|\boldsymbol{v}\|)$
dynamic reachability	needs a stiff grid to track frequency	can operate in islanded mode & black-start grid

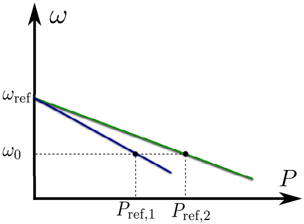
. . . **feedforward-controlled** (constant) power and voltage sources are forming & following → for many reasons **feedback control** is preferable

Limitations of grid-following control

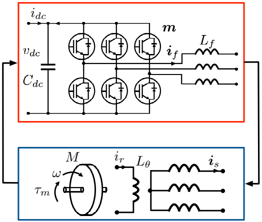


- **is good for** transferring power to a strong grid (main underlying assumption)
- **is not good for** providing a voltage reference, stabilization, or black start
- **prevalent today, but not tomorrow** : what if everyone is a follower . . . ?

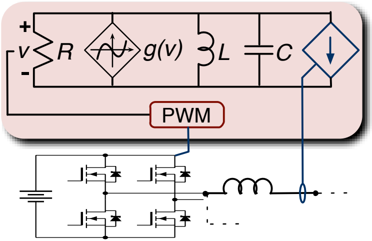
Overview of grid-forming control strategies



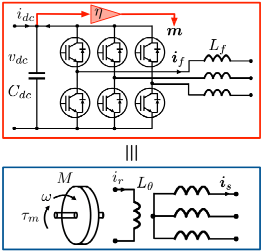
droop control



virtual synchronous machine

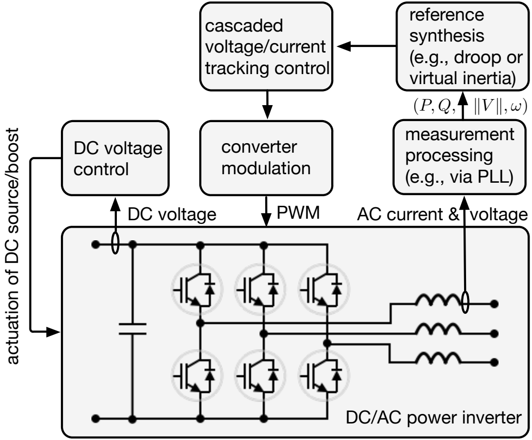


virtual oscillator control (VOC)



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

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**

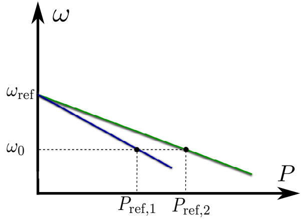
Droop as simplest reference model

- **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:

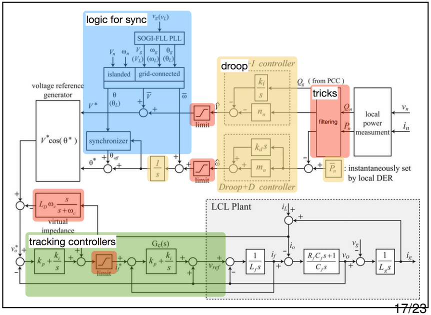
$$\frac{d}{dt}\|v\| = -c_1(\|\boldsymbol{v}\| - v_{\text{ref}}) - c_2(Q - Q_{\text{ref}})$$



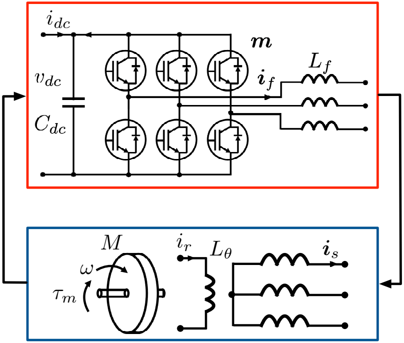
→ direct control of (P, ω) and $(Q, \|\boldsymbol{v}\|)$ **assuming they are independent** (approx. true only near steady state)

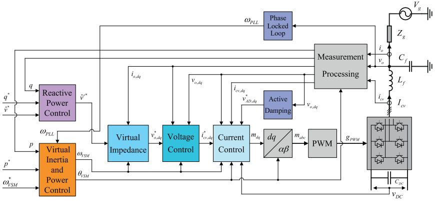
→ ignores DC **source dynamics**

→ requires **tricks in implementation** : low-pass filters for dissipation, virtual impedances for saturation, limiters,. . .



Virtual synchronous machine emulation





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

- **reference** : detailed model of synchronous generator + controls
- **implementation** similar as droop but with even more inner loops . . . tricks

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

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

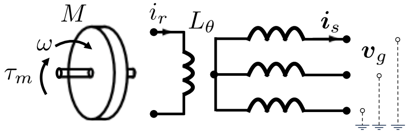
→ **poor fit** for converter:

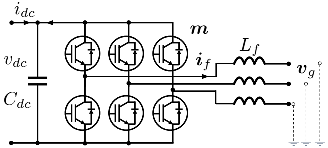
  - converter: **fast** actuation & **no** significant **energy storage**
  - machine: **slow** actuation & significant **energy storage**

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

→ **performs poorly** post-fault

Seeking more natural control





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

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

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

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

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

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

matching energy conversion

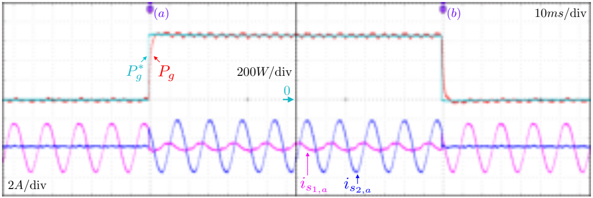
→ **duality:** $C_{\mathrm{dc}} \sim M \sim$ inertia

& $v_{\mathrm{dc}} \sim \omega \sim$ imbalance

\+ **energy shaping** for m_{ampl}

→ theoretical certificates

→ implementation @ETHZ



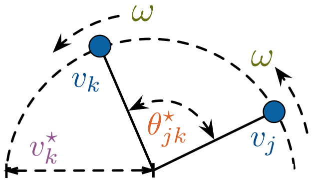
Virtual oscillator control (VOC)

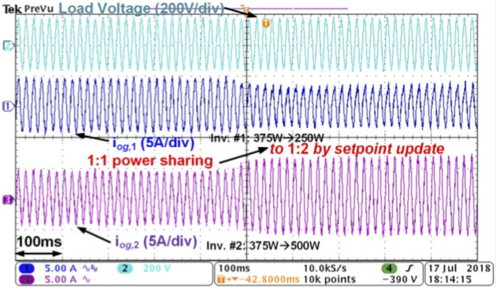
desirable **synchronization mechanism**:

$$\frac{d}{dt}\boldsymbol{v_k} = \underbrace{\begin{bmatrix} 0 & \omega \\ -\omega & 0 \end{bmatrix} \boldsymbol{v_k}}_{\text{rotation at } \omega} + k_1 \cdot \underbrace{\left(v_k^{\star 2} - \|\boldsymbol{v}_k\|^2\right) \boldsymbol{v}_k}_{\text{amplitude regulation to } v_k^\star}$$

$$+ \underbrace{k_2 \cdot \sum_{j=1}^{n} w_{jk} \left(\boldsymbol{v}_j - \begin{bmatrix} \cos(\theta_{jk}^\star) & -\sin(\theta_{jk}^\star) \\ \sin(\theta_{jk}^\star) & \cos(\theta_{jk}^\star) \end{bmatrix} \boldsymbol{v}_k \right)}_{\text{synchronization to desired relative angles } \theta_{jk}^\star}$$

Converter **control specifications**:





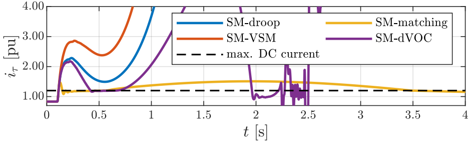
→ **decentralized(!) implementation** of VOC as a reference model using only local measurements & power set-points

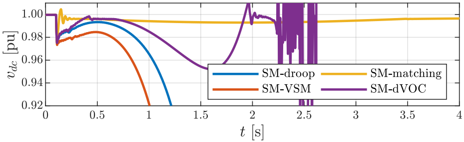
→ **almost global stability** certificate (also when including inner loops)

→ **droop behavior** $P \leftrightarrow \omega$ & $Q \leftrightarrow \|\boldsymbol{v}\|$

→ **experimental validation** @NREL shows robust & agile performance

Comparison of control strategies @AIT





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

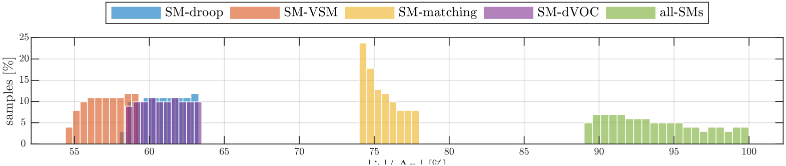
Ali Tayyebi, Dominic Groß, Adolfo Anta, Friederich Kupzog and Florian Dörfler

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

  matching > VOC > droop > virtual synchronous machine

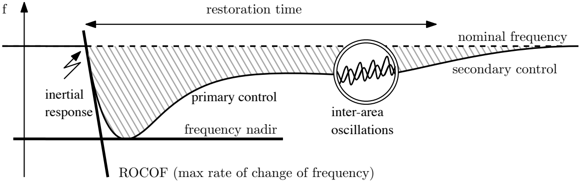
→ it is a very poor strategy for a converter to emulate a flywheel

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

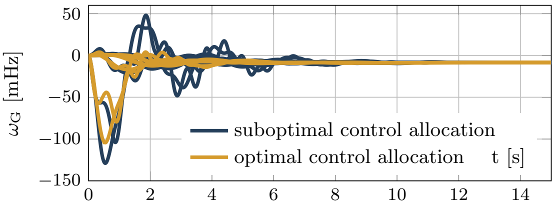


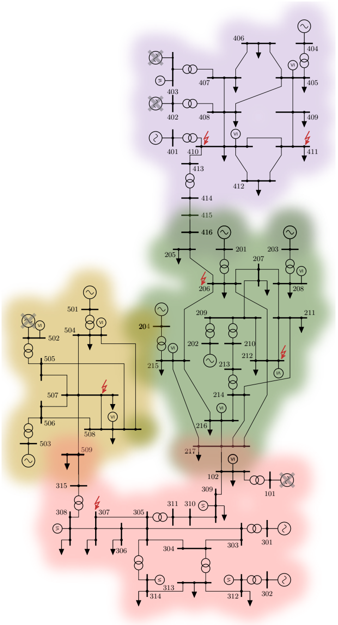
System-level optimization

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



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





Conclusions

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

→ **power systems provide a unique opportunity for the control community**