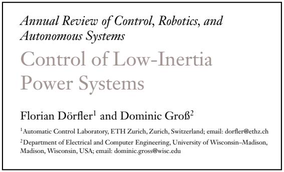
Fundamentals for IBR Control

Florian Dörfler, ETH Zürich

Imperial Summer School on IBR-dominated Power Systems, 2024

Acknowledgements & online resources


Annual Review of Control, Robotics, and Autonomous Systems

Control of Low-Inertia Power Systems

Florian Dörfler[1] and Dominic Groß[2]

[1]Automatic Control Laboratory, ETH Zurich, Zurich, Switzerland; email: dorfler@ethz.ch
[2]Department of Electrical and Computer Engineering, University of Wisconsin–Madison, Madison, Wisconsin, USA; email: dominic.gross@wisc.edu

paper reference for today

detailed grad school material [link]

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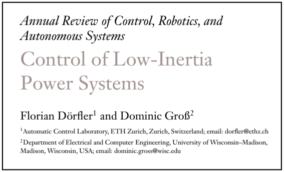
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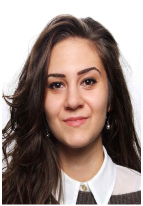
Verena Häberle


Irina Subotic


Ali Tayyebi


Xiuqiang He

detailed grad school material [link]


Eduardo Prieto


Catalin Arghir


Meng Chen


Dominic Groß

On the contents

this topic is a world in itself & there’s lot’s to say

$\longrightarrow$ we will cover selected aspects from the foundations to contemporary research

…& while orthogonal to previous talks

Outline

- Motivation: Challenges & Game Changers
- Power Converter Modeling & Control Specifications
- **Device-Level: Control of Converter-Interfaced Generation**
  - grid-forming
  - cross-forming
- System-Level: Ancillary Services in Low-Inertia Grids

We will use the board

be prepared to take notes

Outline

- Motivation: Challenges & Game Changers
- Power Converter Modeling & Control Specifications
- **Device-Level: Control of Converter-Interfaced Generation**
- System-Level: Ancillary Services in Low-Inertia Grids

Replacing the system foundation

fuel

− **not sustainable**

renewables

+ **sustainable**

Replacing the system foundation

fuel

− **not sustainable**

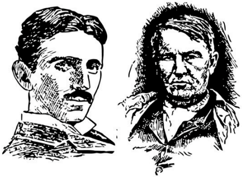
+ **central & dispatchable** generation

renewables

+ **sustainable**

− **distributed & variable** generation

Replacing the system foundation



fuel & synchronous machines

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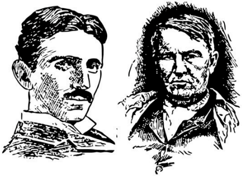


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renewables & power electronics

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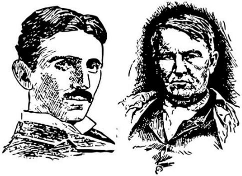

fuel & synchronous machines

- − **not sustainable**
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- \+ **self-synchronize** through the **grid**

renewables & power electronics

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- − **distributed & variable** generation
- − almost **no energy storage**
- − **no** inherent **self-synchronization**

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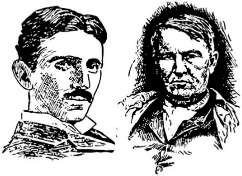

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renewables & power electronics

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− **distributed & variable** generation

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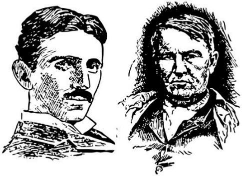

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+ **central & dispatchable** generation

+ **large** rotational **inertia** as buffer

+ **self-synchronize** through the **grid**

+ **resilient** voltage / frequency **control**

− **slow** actuation & **control**

renewables & power electronics

+ **sustainable**

− **distributed & variable** generation

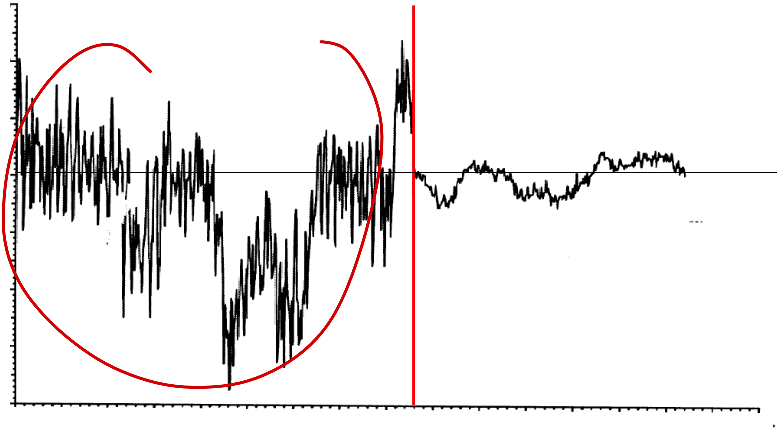
− almost **no energy storage**

− **no** inherent **self-synchronization**

− **fragile** voltage / frequency **control**

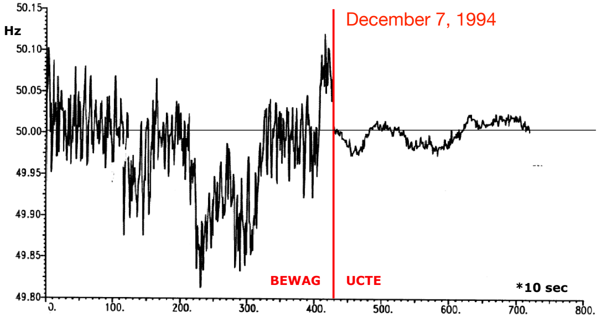
+ **fast / flexible / modular control**

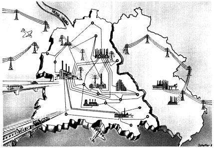
What do we see here ?



West Berlin re-connecting to Europe

Source: *Energie-Museum Berlin*

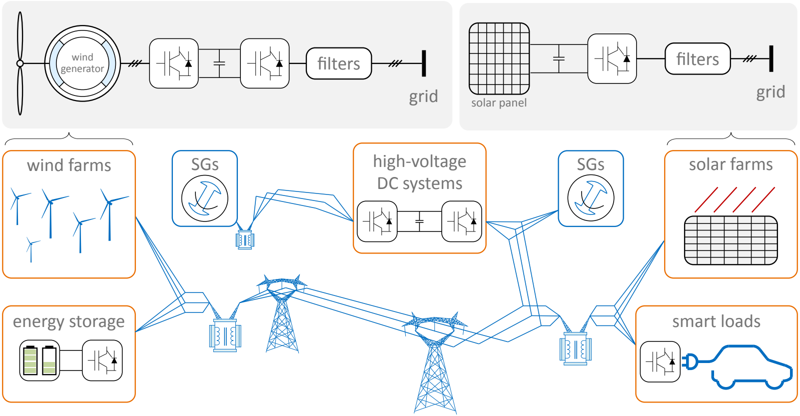




before re-connection: islanded operation based on **batteries** & boiler

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

Power-electronics-dominated power systems



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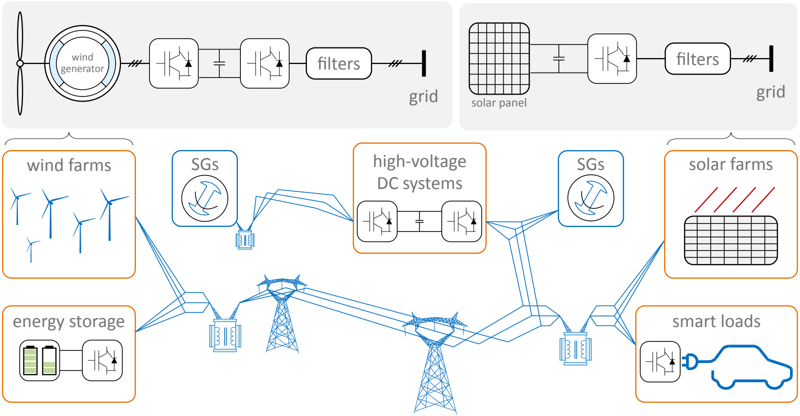

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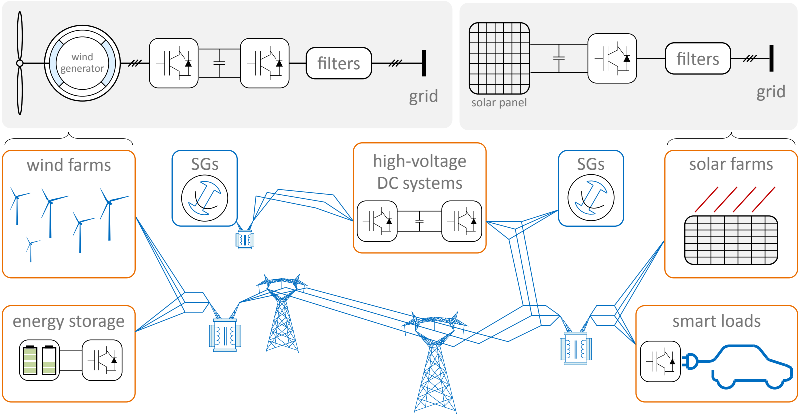

- relevant observation: system enabled by ubiquitous actuation, pervasive sensing, & digitalization, i.e., **control**, rather than clever physical design
- aggressive integration of technology $\rightarrow$ ***system issues***: oscillations, lack of inertia ($\rightarrow$ RoCoF limits) & reactive power ($\rightarrow$ SE Australia outages), …

Issues are by now broadly recognized

- **low-inertia issues were not really on the radar** (outside few places, e.g., Ireland or Oz) until ten years ago

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→ led to outages & comical situations ...

Biblis A generator stabilizes the grid as a synchronous condenser amprion SIEMENS

USING DECOMMISSIONED NUCLEAR POWER PLANT AS SYSTEM SERVICE PROVIDERS

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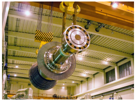
Energiforsk



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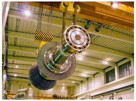

new challenges: low-inertia stability, grid-forming control, & fast frequency support

→ industry willing to explore **green-field approach** & join forces with academia

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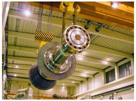

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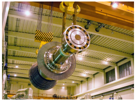

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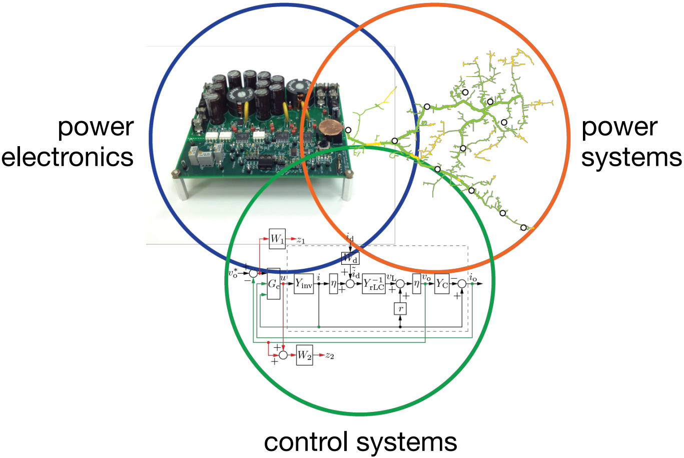
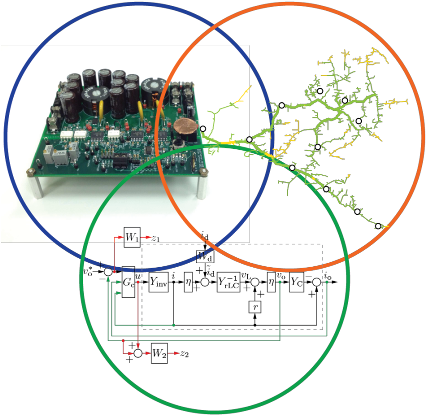
- across the pond: unifi consortium

Exciting research bridging communities



Exciting research bridging communities

power electronics



power systems

control systems

theory ↔ practice | device ↔ system | proof ↔ experiment

Conclusion: re-visit models/analysis/control

plenty of surveys from the power electronics / power systems / control communities

Foundations and Challenges of Low-Inertia Systems

(Invited Paper)

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* also University of Hong Kong
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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.

Annual Review of Control, Robotics, and Autonomous Systems

Stability and Control of Power Grids

Tao Liu,[1,*] Yue Song,[1,*] Lipeng Zhu,[1,2,*] and David J. Hill[1,3]

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[2]College of Electrical and Information Engineering, Hunan University, Changsha, China; email: zhulpwhu@126.com
[3]School of Electrical Engineering and Telecommunications, University of New South Wales, Kensington, New South Wales, Australia

Power systems without fuel

Josh A. Taylor[a,*], Sairaj V. Dhople[b,1], Duncan S. Callaway[c]

[a] Electrical and Computer Engineering, University of Toronto, Toronto, Canada ON M5S 3G4
[b] Electrical and Computer Engineering, University of Minnesota, Minneapolis, MN 55455, USA
[c] Energy and Resources Group, University of California, Berkeley, CA 94720, USA

Fundamentals of power systems modelling in the presence of converter-interfaced generation

Mario Paolone[a,*], Trevor Gaunt[b], Xavier Guillaud[c], Marco Liserre[d], Sakis Meliopoulos[e], Antonello Monti[f], Thierry Van Cutsem[g], Vijay Vittal[h], Costas Vournas[i]

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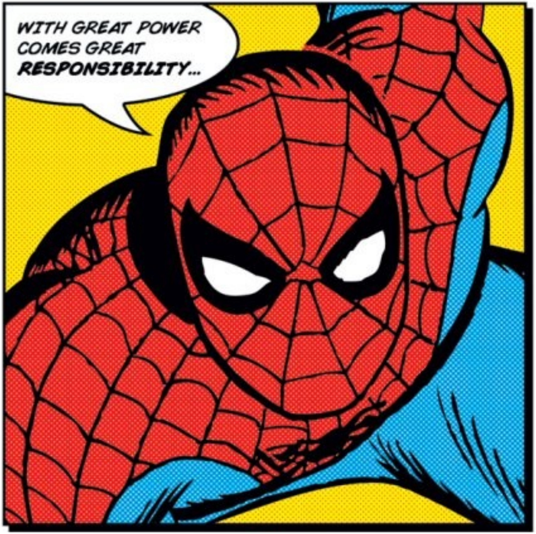
Power system stability in the transition to a low carbon grid: A techno-economic perspective on challenges and opportunities

Lasantha Meegahapola[1] | Pierluigi Mancarella[2,3] | Damian Flynn[4] | Rodrigo Moreno[5,6,7]

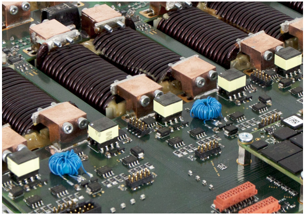
On the Inertia of Future More-Electronics Power Systems

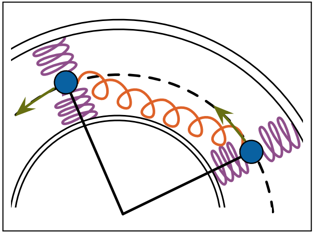
Jingyang Fang, *Student Member, IEEE*, Hongchang Li, *Member, IEEE*, Yi Tang, *Senior Member, IEEE*, and Frede Blaabjerg, *Fellow, IEEE*

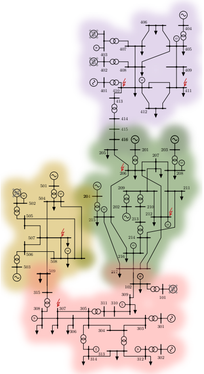
A unique opportunity for systems & control



Focus of today's tutorial







modeling, control specifications, & game changers

- focus: fast time scales & old versus new
- power system/converter control specifications & limitations

decentralized control of power converters

- hierarchical control architectures & grid-forming versus grid-following
- grid-forming: VSM, droop, matching, & VOC + over-current protection

effect of local controls in large-scale systems

- ancillary service perspective & performance metrics
- allocation of inertia / damping & dynamic virtual power plants

Outline

- Motivation: Challenges & Game Changers
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- **Device-Level: Control of Converter-Interfaced Generation**
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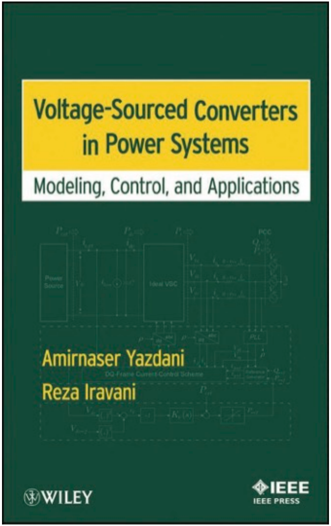
modeling

If you want a detailed reference on power electronics dc/ac conversion

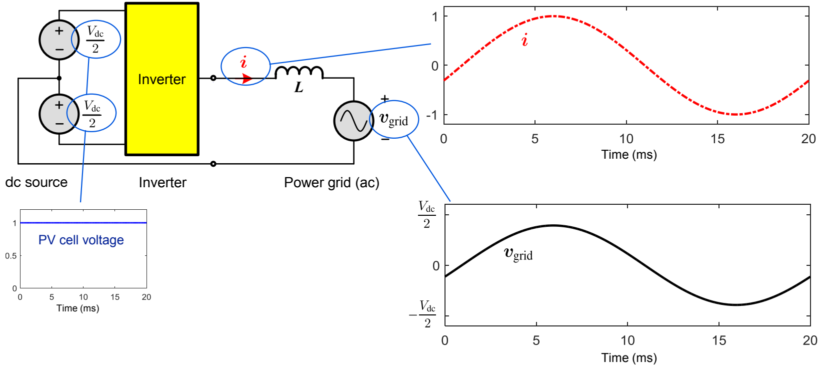


Power electronics dc/ac conversion basics

adapted from slides by Tobias Geyer (ABB & ETH Zürich)

abstract dc-to-ac power conversion

objective: transfer power to the grid



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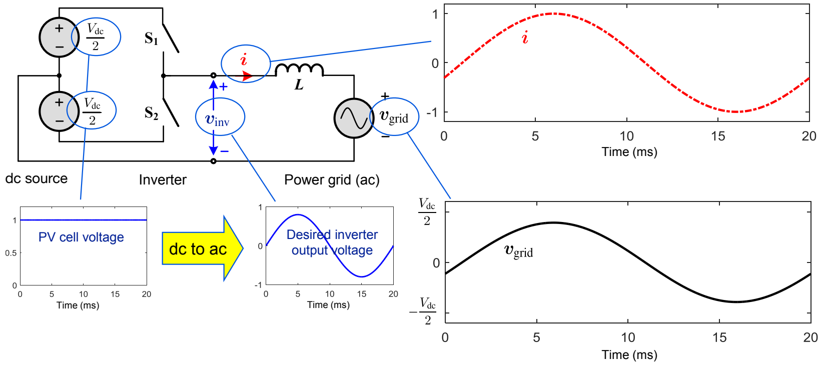
2-level inverter with idealized switches

objective: transfer power to the grid



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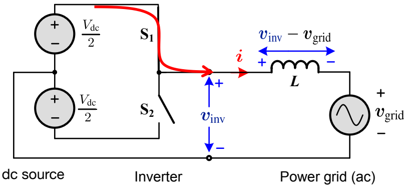

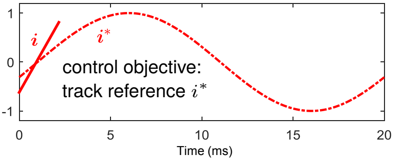

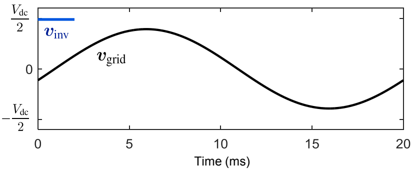

The switches are operated dually:

- S_1 on and S_2 off: $v_{inv} = V_{dc}/2$

  => the current **increases** proportional to the voltage difference:

$$L \frac{d}{dt} i(t) = v_{inv}(t) - v_{grid}(t)$$

Power electronics dc/ac conversion basics

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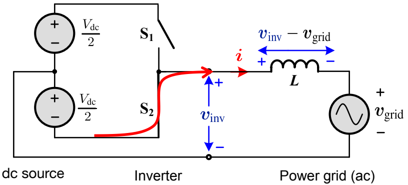

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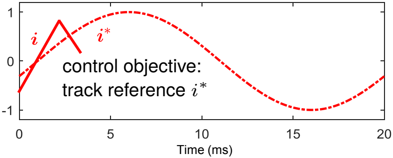
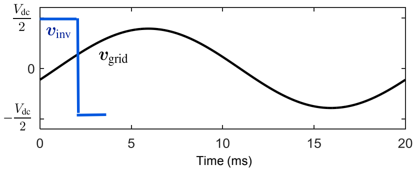
objective: transfer power to the grid





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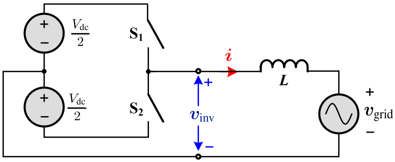

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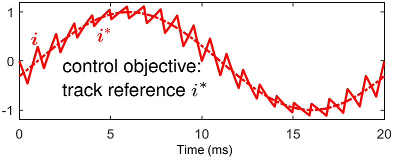
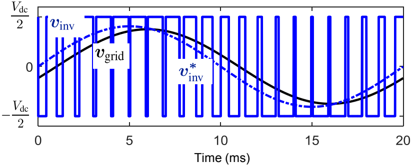


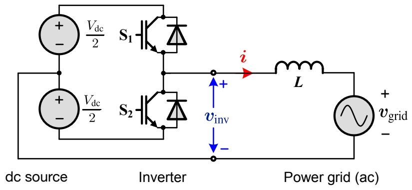


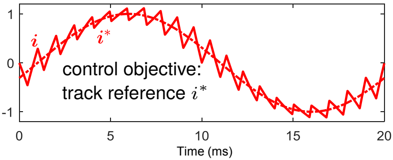
Power electronics dc/ac conversion basics

adapted from slides by Tobias Geyer (ABB & ETH Zürich)

inverter with semi-conductor switches

objective: transfer power to the grid





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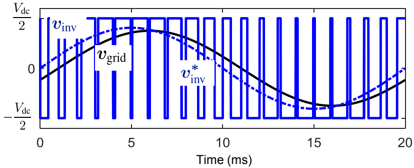

Remarks on power electronics conversion

- there are many strategies for **pulse-width modulation**:
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- on average $v_{\text{inv}} \approx v_{\text{inv}}^{\star}$

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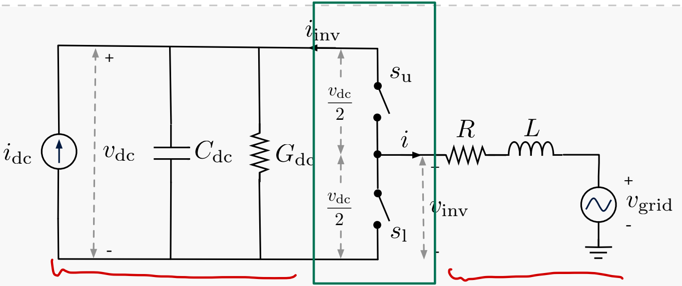
  precise by **averaging theory** (see board for details)

Average-switch modeling of converters

(covered on the board)



dc dynamics: $C_{dc}\dot{v}_{dc} = -G_{dc}v_{dc} + i_{dc} - i_{inv}$

ac dynamics: $\frac{d}{dt} L i = -R i + v_{inv} - v_{grid}$

switches: $s_u, s_l \in \{0, 1\}$

$s_u + s_l = 1$

$v_{inv} = \frac{v_{dc}}{2}(s_u - s_l)$

"Averaging" of the ac dynamics:

assume that V_{inv} is T-periodic

$$\Rightarrow \quad V_{inv} = \underbrace{\frac{1}{T}\int_0^T V_{inv}(\tau)\, d\tau}_{\bar{V}_{inv}} + \underbrace{\sum_{k=1}^{\infty} a_k \cos\left(\frac{2\pi}{T}\cdot k\cdot t\right) + b_k \sin\left(\frac{2\pi}{T}\cdot k \cdot t\right)}_{\text{higher-order terms from Fourier series}}$$

superposition of ac currents: $i = \underbrace{\bar{i}}_{\text{the average}} + \tilde{i}$

where $\bar{i}$ follows the average dynamics:

$$\frac{d}{dt} L \bar{i} = - R \bar{i} + \bar{V}_{inv} - V_{grid}$$

and $\tilde{i}$ follows the higher-order dynamics

$$\underbrace{\frac{d}{dt} L \tilde{i} = - R \tilde{i}}_{\text{low-pass with cut-off frequency } R/L} + \text{"Fourier series"}$$

} if $R/L \ll \frac{2\pi}{T}$, then $\tilde{i} = \mathcal{O}(1/T) \approx 0$

⇝ apply averaging to all signals and drop higher harmonics:

$$\frac{d}{dt} L \bar{i} = - R \bar{i} + \underbrace{\bar{v}_{inv}} - v_{grid} \qquad \bar{s}_u + \bar{s}_\ell = 1$$

$$\bar{v}_{inv} = \frac{v_{dc}}{2} \left(\bar{s}_u - \bar{s}_\ell \right) = \frac{v_{dc}}{2} \left(2 \bar{s}_u - 1 \right)$$

$$= v_{dc} \underbrace{\left(\bar{s}_u - \tfrac{1}{2} \right)}$$

$$\Rightarrow \boxed{\frac{d}{dt} L \bar{i} = - R \bar{i} + m \, v_{dc} - v_{grid}}$$

modulation index

$m \in [-\tfrac{1}{2}, +\tfrac{1}{2}]$

continuous after averaging

dc dynamics: $C_{dc} \dot{v}_{dc} + G_{dc} v_{dc}$

$$= i_{dc} - \bar{i}_{inv} = i_{dc} - m \bar{i}$$

power balance accross the lossless switches

$\bar{i}_{inv} = m \bar{i}$

$$P_{dc} = P_{ac} : \bar{i}_{inv} \cdot v_{dc} = \bar{v}_{inv} \, \bar{i} = m \cdot v_{dc} \cdot \bar{i}$$

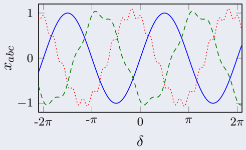
Modeling review: signal space in 3-phase

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

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



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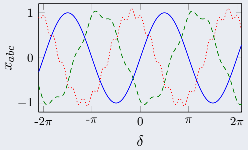
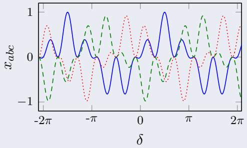


balanced (nearly true)

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

so that

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



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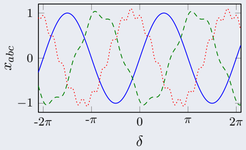

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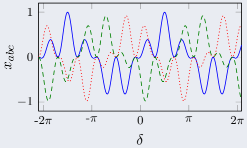
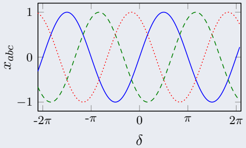


synchronous (desired)

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

const. freq & amp

$\Rightarrow$ const. in rot. frame



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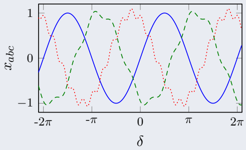

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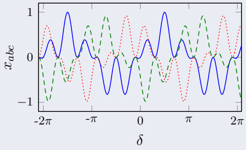

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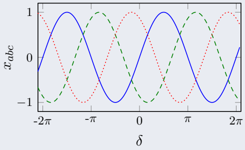

assumption : balanced $\Rightarrow$ 2d-coordinates $x(t) = [x_\alpha(t)\, x_\beta(t)]$ or $x(t) = A(t) \cdot e^{i\delta(t)}$

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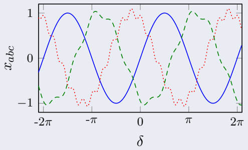

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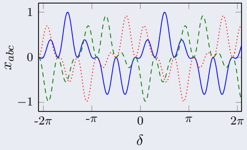

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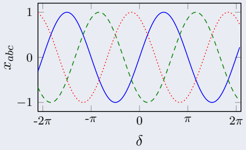

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current/voltage $\rightarrow$ **power**: active $p = v^\top i$ and reactive $q = v^T \left[\begin{smallmatrix} 0 & -1 \\ 1 & 0 \end{smallmatrix}\right] i = v \times i$

Transforms of 3-phase balanced signals

x_{abc}

$$\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} = \begin{bmatrix} \sin(\delta) \\ \sin(\delta - \frac{2\pi}{3}) \\ \sin(\delta + \frac{2\pi}{3}) \end{bmatrix}$$

$\rightarrow$ orthogonal to $\begin{bmatrix} 1 & 1 & 1 \end{bmatrix}$

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removing the balanced subspace $\begin{bmatrix} 1 & 1 & 1 \end{bmatrix}$

$$T_{\alpha\beta\gamma} = \sqrt{\frac{2}{3}} \left[\begin{array}{ccc} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \hline \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{array}\right]$$

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→ x_γ often discarded & $x_{\alpha\beta}$ shown as phasor $e^{\mathrm{i}(\delta - \frac{\pi}{2})}$

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orthonormal **Park transform**: $x_{\alpha\beta\gamma} \rightarrow x_{dq0}$
into rotating frame with angle θ

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$$x_{dq0} = T_{dq0}\, x_{\alpha\beta\gamma}$$

$$\begin{bmatrix} x_d \\ x_q \\ \hline x_0 \end{bmatrix} = \sqrt{\tfrac{3}{2}} \begin{bmatrix} \sin(\theta + \delta) \\ -\cos(\theta + \delta) \\ \hline 0 \end{bmatrix}$$

$\rightarrow$ typical choice $\theta = -\delta$

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Transforms of 3-phase balanced signals

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$\rightarrow$ orthogonal to $\begin{bmatrix} 1 & 1 & 1 \end{bmatrix}$

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

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$x_{\alpha\beta\gamma} = T_{\alpha\beta\gamma} \, x_{abc}$

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$\rightarrow$ typical choice $\theta = -\delta$

$x_{dq0} = T_{dq0} \cdot T_{\alpha\beta\gamma} \, x_{abc}$ with overall transform

$$\sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos\left(\theta + \frac{2\pi}{3}\right) & \cos\left(\theta - \frac{2\pi}{3}\right) \\ \sin(\theta) & \sin\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta - \frac{2\pi}{3}\right) \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix}$$

it’s tedious but useful to work through these calculations once in your lifetime

$\alpha\beta\gamma \rightarrow dq0$ & rotation matrix tricks

(covered on the board)

- sign convention $R(\theta) = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix}$ $e^{j\theta}$

$R(-\theta) = \begin{bmatrix} \cos\theta & +\sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} = R(\theta)^T = (R(\theta))^{-1}$

- key identity: $R(\theta) \cdot R(\delta) = R(\theta + \delta)$

$R(\theta) \cdot R(-\theta) \cdot R(\theta - \theta) = I$

$\sqrt{-1} = j$

- analog of imaginary unit: $J = R(\pi/2) = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$

$\llcorner$ $j = e^{i\pi/2}$

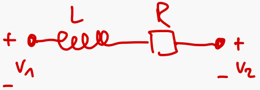
$j^2 = -1$: $J \cdot J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} = \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix} = -I$

- derivative rule

$$\frac{d}{dt} R(\theta(t)) = \frac{d}{dt} e^{i\theta(t)} = i\dot{\theta} e^{i\theta(t)} = \dot{\theta} \cdot J \cdot R(\theta(t))$$

$$L\dot{i} = L\dot{i} = L \backslash dot \backslash iota = L\dot{i}$$

- application to circuits



$$\alpha\beta: \quad \frac{d}{dt} L i = -R i + v_1 - v_2$$

transform from $\alpha\beta$ into dq coordinates with const. frequ. ω

$$I = R(-\omega t)\, i, \quad V_k = R(-\omega t)\, v_k$$

$$\frac{d}{dt} L I = L \frac{d}{dt}\left(R(-\omega t) \cdot i\right) = L \frac{d}{dt} R(-\omega t)\, i$$

$$+ L R(-\omega t) \frac{d}{dt} i = L J \omega R(-\omega t)\, i + R(-\omega t) \cdot (-R i + v_1 - v_2)$$

$$= -(R + J\omega L)\, I + V_1 - V_2$$

Modeling: voltage source converter

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

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

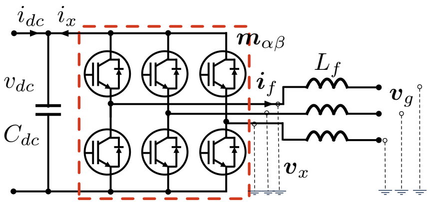
3. **power electronics modulation**

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

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

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

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

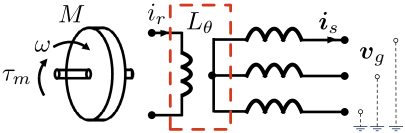


$$C_{\text{dc}} \frac{\mathrm{d} v_{\text{dc}}}{\mathrm{d}t} = -G_{\text{dc}} v_{\text{dc}} + i_{\text{dc}} + \boldsymbol{m}^\top \boldsymbol{i}_f$$

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

comparison to synchronous machine

Modeling: synchronous machine



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

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

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

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 $\boldsymbol{v}_g$

Energy-based modeling & insights

(covered on the board)

converter:

$$\begin{cases} C_{\text{dc}} \dfrac{\mathrm{d}v_{\text{dc}}}{\mathrm{d}t} = -G_{\text{dc}} v_{\text{dc}} + i_{\text{dc}} + \boldsymbol{m}^\top \boldsymbol{i}_f \\ L_f \dfrac{\mathrm{d}\boldsymbol{i}_f}{\mathrm{d}t} = -R_f \boldsymbol{i}_f + \boldsymbol{v}_g - \boldsymbol{m}\, v_{\text{dc}} \end{cases}$$

energy: $E = \frac{1}{2} v_{dc}^2 C_{dc} + \underbrace{\frac{1}{2} L_f i_f^2}_{\approx 0}$

power balance: $\frac{d}{dt} E = \underbrace{- \begin{bmatrix} v_{dc} \\ i_f \end{bmatrix}^T \begin{bmatrix} G_{dc} & \\ & R_f \end{bmatrix} \begin{bmatrix} v_{d} \\ i_c \end{bmatrix}}_{\text{dissipation}} \underbrace{+ i_{dc} \cdot v_{dc} + i_f \cdot v_g}_{\text{ac/dc power supplies}}$

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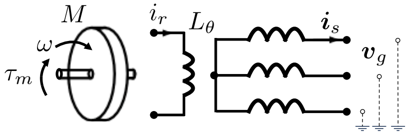
$$E = \frac{1}{2} M \omega^2 + \frac{1}{2} i_f^T L(\theta) i_f$$

$$\frac{d}{dt} E = - \begin{bmatrix} \omega \\ i_s \end{bmatrix}^T \begin{bmatrix} D & \\ & -R_s \end{bmatrix} \begin{bmatrix} \omega \\ i_s \end{bmatrix}$$

$$+ \tau_w \cdot \omega + i_s \cdot v_g$$

Comparison: storage & conversion mechanisms



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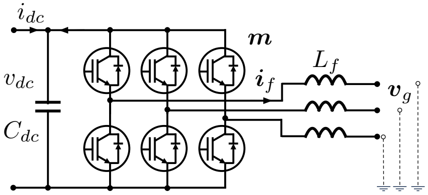

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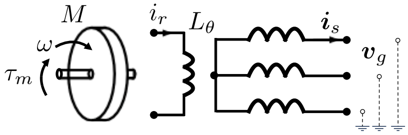

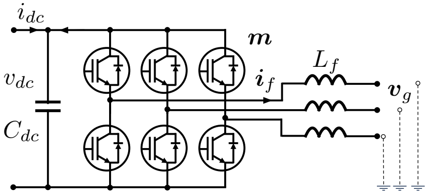

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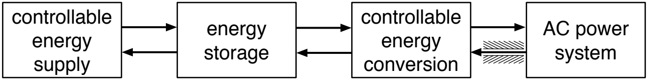
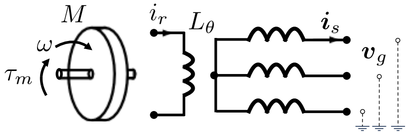


τ_m (slow) vs. i_{dc} (fast)	M (large) vs. C_{dc} (small)	L_θ (physical) vs. $\boldsymbol{m}$ (control)	resilient vs. fragile

Comparison: storage & conversion mechanisms



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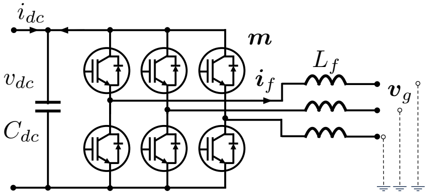

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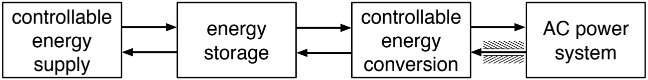

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resilient vs. fragile

physical & robust
vs.
controlled & agile
energy conversion
& (kinetic) **storage**

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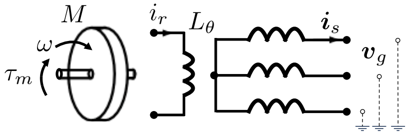

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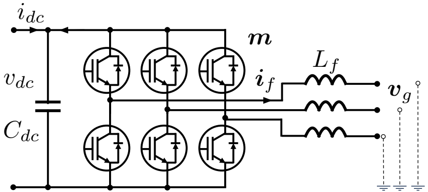

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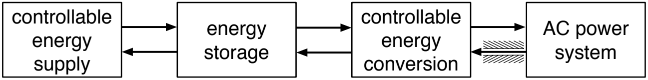

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physical & robust
vs.
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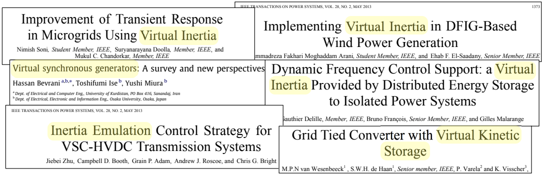
energy conversion
& (kinetic) **storage**

anti-podal characteristics $\Longrightarrow$ **do not use a converter to emulate a machine**

Preview: pitfalls of naive inertia emulation

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



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mmadreza Fakhari Moghaddam Arani, *Student Member, IEEE*, and Ehab F. El-Saadany, *Senior Member, IEEE*

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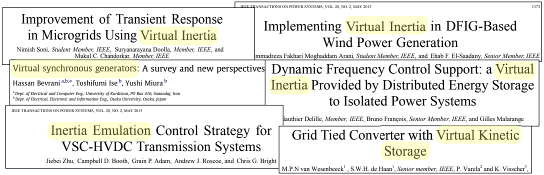
. . . can & has been done **but**
recall **antipodal characteristics**



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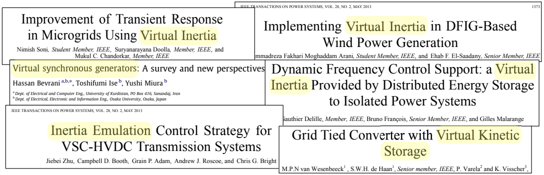
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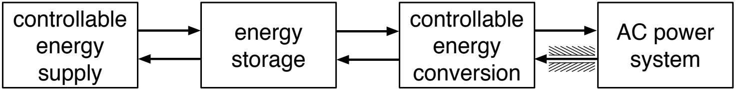

slow vs. fast | large vs. small | physics vs. control | resilient vs. fragile

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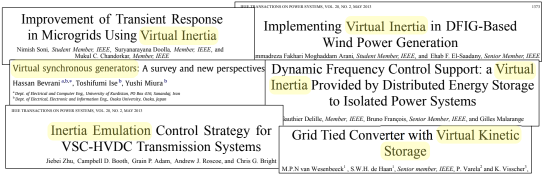
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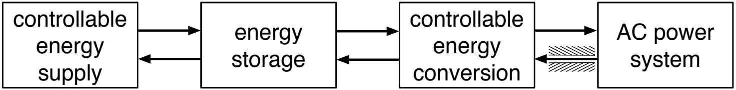
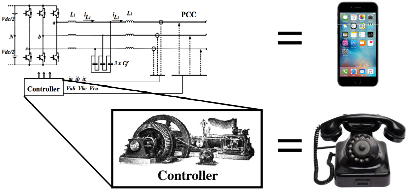


slow vs. fast   large vs. small   physics vs. control   resilient vs. fragile

telecom analogy (E. Mallada)



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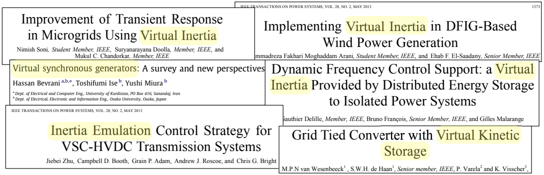
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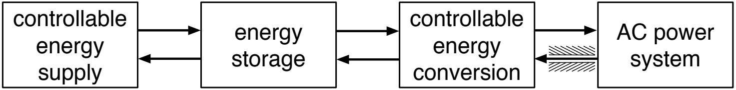

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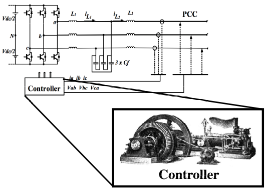

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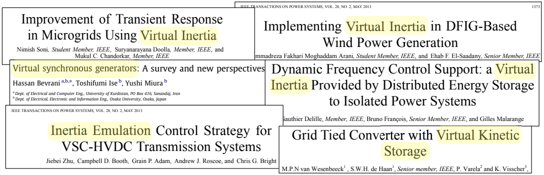
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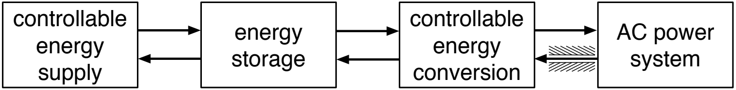
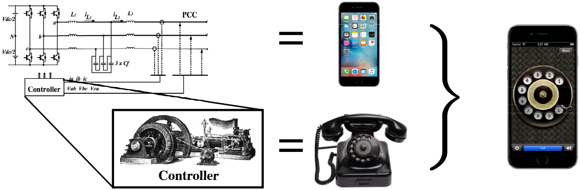


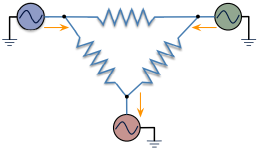
slow vs. fast large vs. small physics vs. control resilient vs. fragile

telecom analogy (E. Mallada)

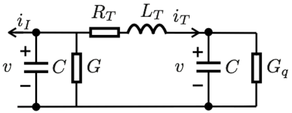
- works (under business-as-usual operation)
- there are better solutions (espec. for contingencies)



Modeling review: the network



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



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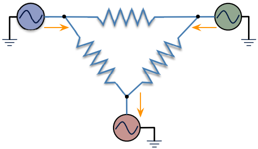

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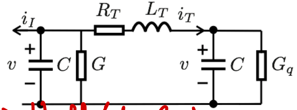
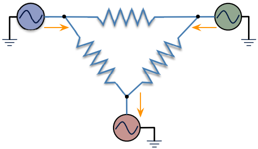


admittance / Kirchhoff / Laplacian

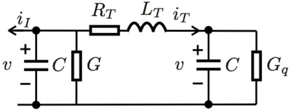
- **conventional assumption:** quasi-steady state **algebraic model**

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

Modeling review: the network



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



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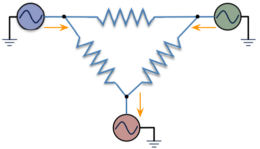

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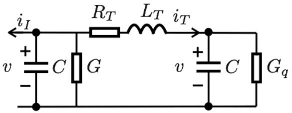

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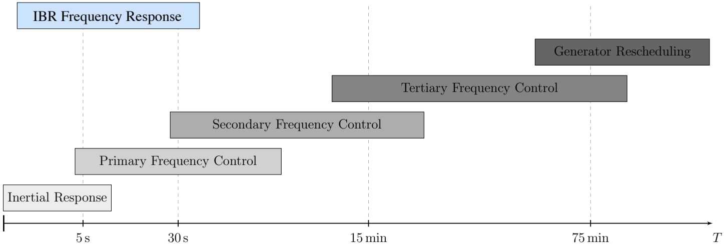
- but quasi-steady-state **assumption is flawed** in low-inertia systems

Time-scale separation issues – old & new

power system operational time scales



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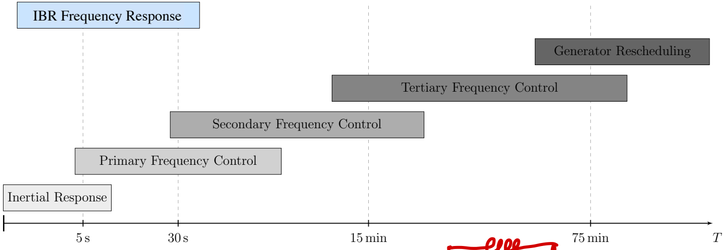
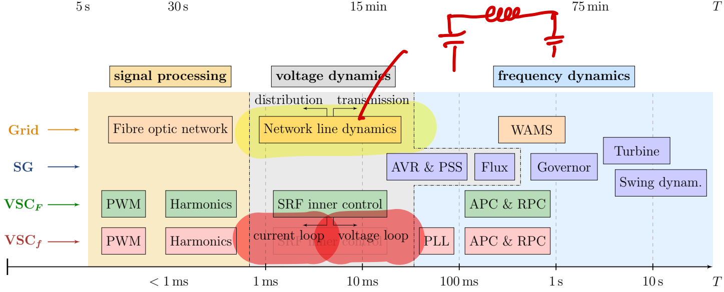


fast time scales: converter/generator controls & physics



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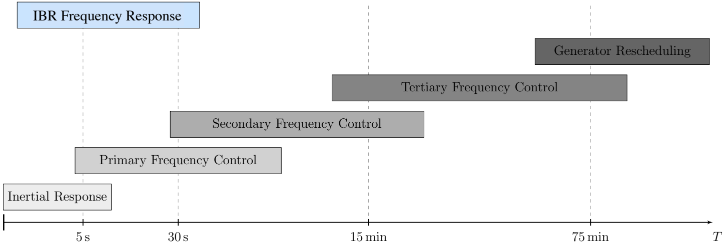
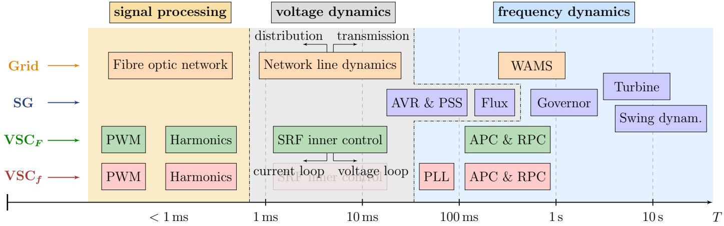


fast time scales: converter/generator controls & physics

→ separated aside from **line dynamics**



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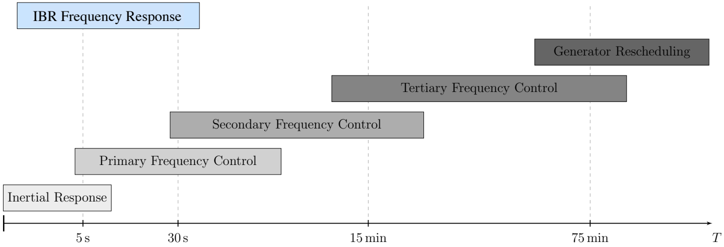

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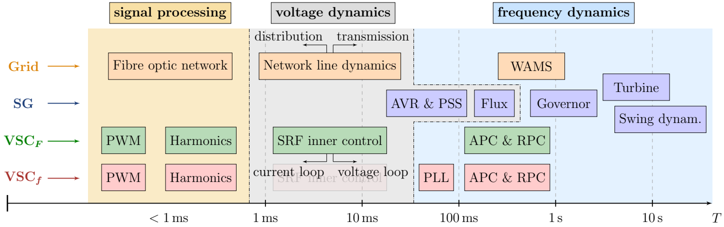

⟶ to avoid issues, model the line dynamics or slow down converter controls !

control specifications & architecture

Control specifications

- **nominal synchronous operation**:
  - constant DC states: $\dot{\omega} = \dot{v}_{\mathrm{dc}} = 0$
  - synchronous AC states at ω_{ref} :
    $\dot{\theta} = \omega_{\mathrm{ref}}, \ \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}_s = \begin{bmatrix} 0 & \omega_{\mathrm{ref}} \\ -\omega_{\mathrm{ref}} & 0 \end{bmatrix} \boldsymbol{i}_s, \ \ldots$
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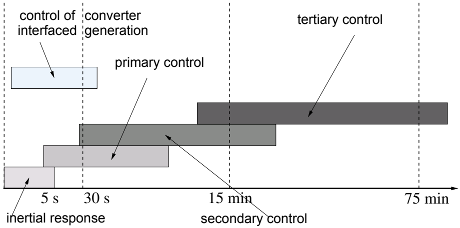

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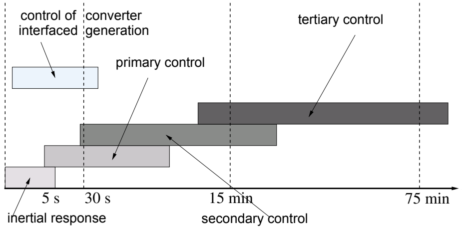

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  passively via physics (inertia) & actively via control

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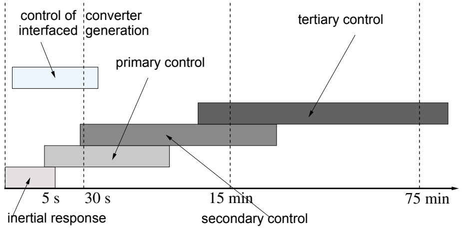

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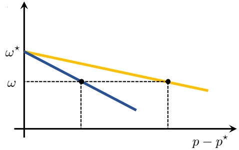
$\rightarrow$ decentralized **droop/primary control** $P - P_{\text{ref}} \propto \omega - \omega_{\text{ref}}$



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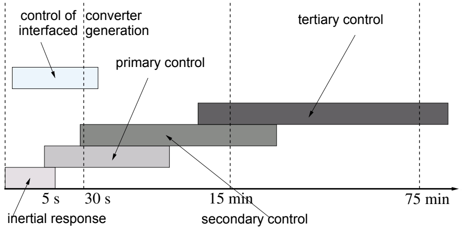

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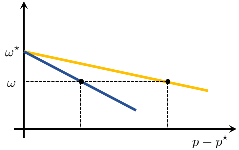

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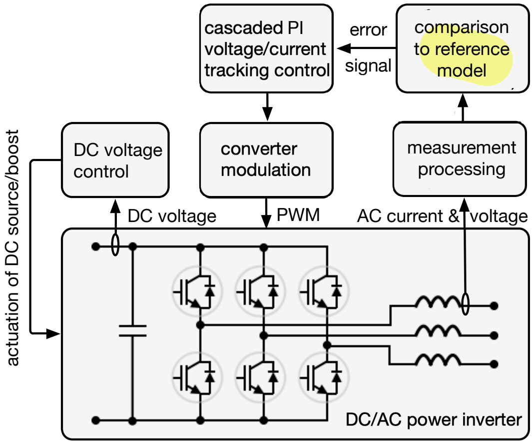
- **secondary control:** regulation of $\omega \rightarrow \omega_{\text{ref}}$ (similar for $\boldsymbol{v}$)
- **tertiary control:** (re)scheduling of set-points

} similar as in conventional power systems

Cartoon of power electronics 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** reference error

   assumption: no state constraints encountered
4. **actuation** via modulation

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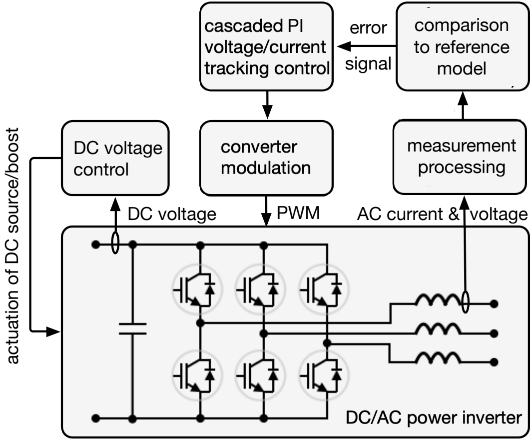

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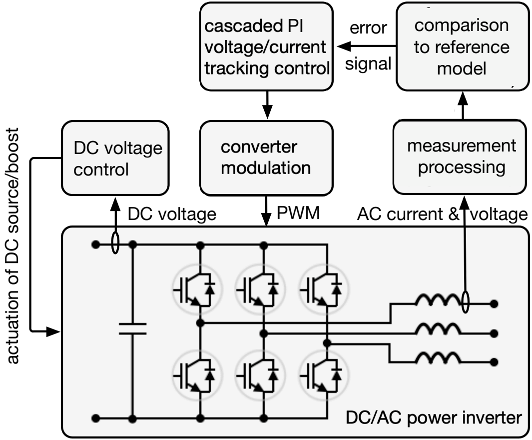

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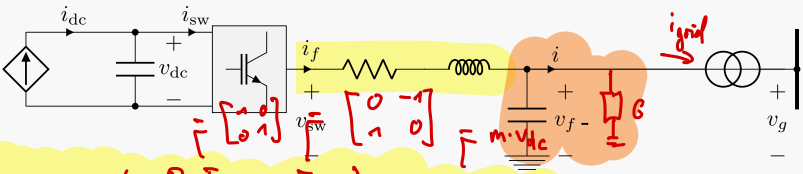
6. plus ***implementation tricks***: saturation via virtual impedance, low-pass filter for dissipation, limiters, dead zones, logic, ...

Hierarchical control architecture

(covered on the board)



$$\frac{d}{dt} L i = (-R I_2 + J\omega L)\, i + v_{sw} - v$$

$$\frac{d}{dt} C v = (-G I_2 + C\omega J)\, v + i - i_{grid}$$

<u>Control objective:</u> v should track a reference v_{ref}

<u>Cascaded PI control</u>: (1) "pretend that we can control v via i"

(2) control i to its reference

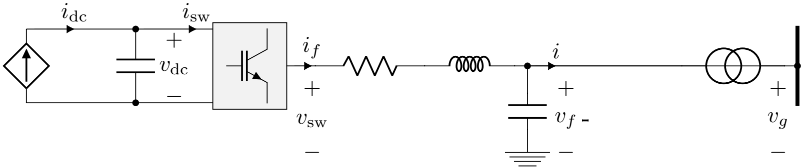
① "voltage loop": calculate an ideal current reference i_{ref} so that $v(t) \to v_{ref}(t)$

$$i_{ref} = \underbrace{i_{grid} + (G I_2 - C\omega J) v}_{\text{feedforward cancellation}} \underbrace{- k_1 (v - v_{ref}) - k_2 \int v - v_{ref}\, dt}_{\text{PI - feedback}}$$

② "current loop": control v_{sw} so that $i(t) \to i_{ref}(t)$

$$v_{sw} = \underbrace{v + (R I_2 + J\omega L) i}_{\text{feedforward cancellation}} - k_3 (i - i_{ref}) - k_4 \int i - i_{ref}\, dt$$

Example: Inner/Outer Control Loops



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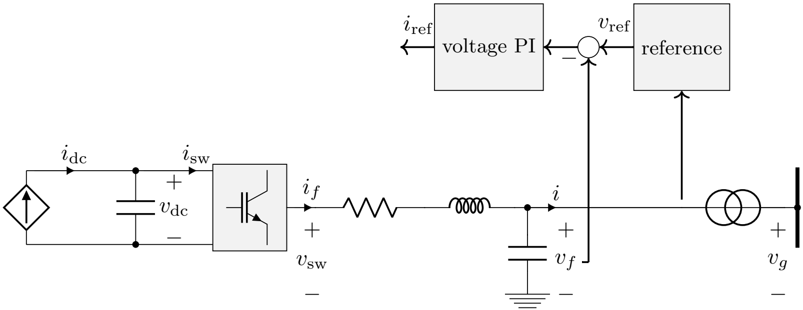

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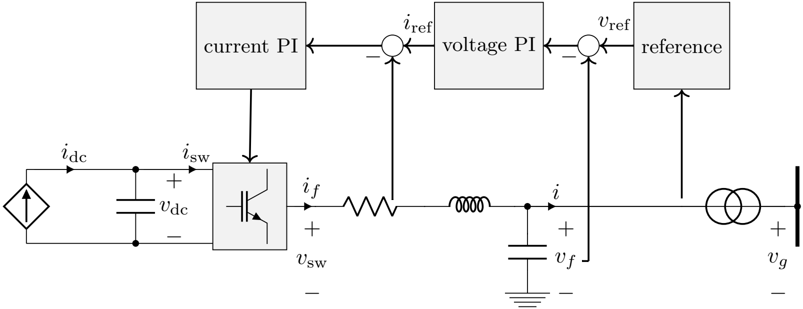

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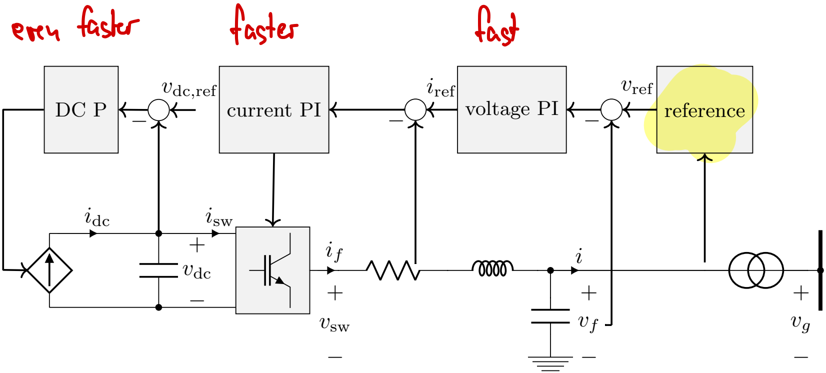
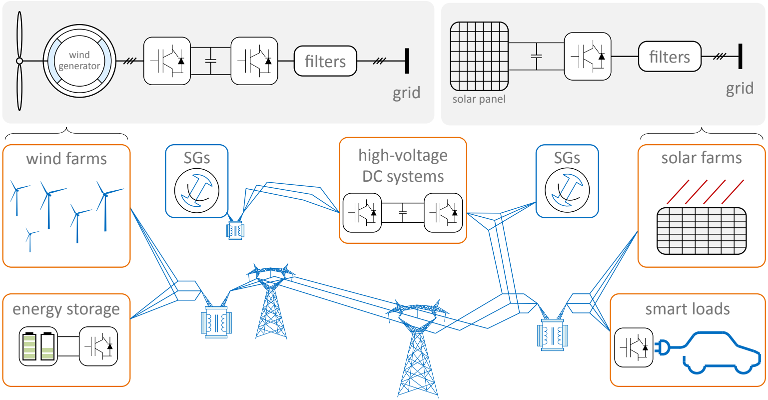


Outline

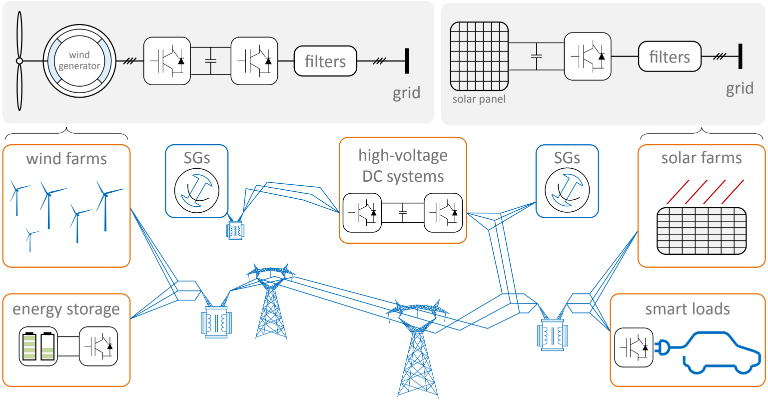
- Motivation: Challenges & Game Changers
- Power Converter Modeling & Control Specifications
- **Device-Level: Control of Converter-Interfaced Generation**
- System-Level: Ancillary Services in Low-Inertia Grids

Device-level challenges with inverter-based sources



- primary source: constrained in active/ reactive power, energy, bandwidth, . . .
- interlinking converters: master vs. slave
- fragile grid-connection (over-currents)
- assuring time-scale separation & avoiding resonances + oscillations
- ...

Device-level challenges with inverter-based sources



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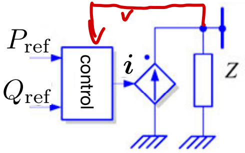
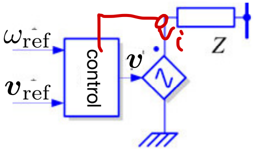
- signal causality: **following vs. forming**

Grid-forming vs. following converter control

	grid-following	grid-forming
converter-type (loose but very common definition)	current-controlled & frequency-following 	voltage-controlled & frequency-forming 
signal causality	$(\omega, \|\boldsymbol{v}\|) \longrightarrow (P, Q)$	$(P, Q) \longrightarrow (\omega, \|\boldsymbol{v}\|)$
dynamic reachability	needs a stiff grid	blackstart & islanded operation
disturbance sensitivity	filters only low frequencies	smoothens high frequencies

grid-forming = "distance to a stiff voltage source"

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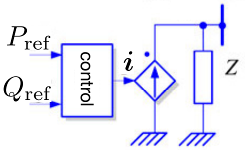
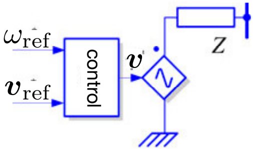
converter-type (loose but very common definition)	current-controlled & frequency-following 	voltage-controlled & frequency-forming 
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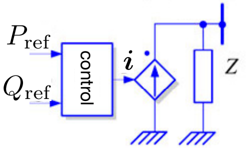
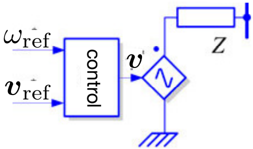
converter-type (loose but very common definition)	current-controlled & frequency-following 	voltage-controlled & frequency-forming 
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$\longrightarrow$ **stiff voltage sources** are obviously perfectly grid-forming, but do not react to imbalances $\longrightarrow$ for many reasons **feedback control** is preferable

Remark: definitions are debated

- put 20 experts in a room ... $\rightarrow$ **no universal definition** & many hybrid concepts
- agreement on fact: power systems **need XXX% of grid-forming sources**

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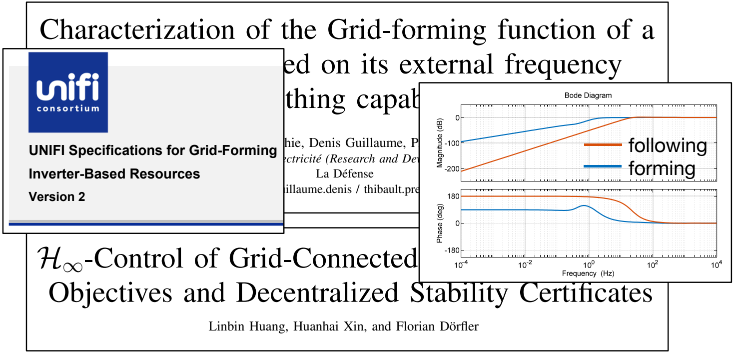
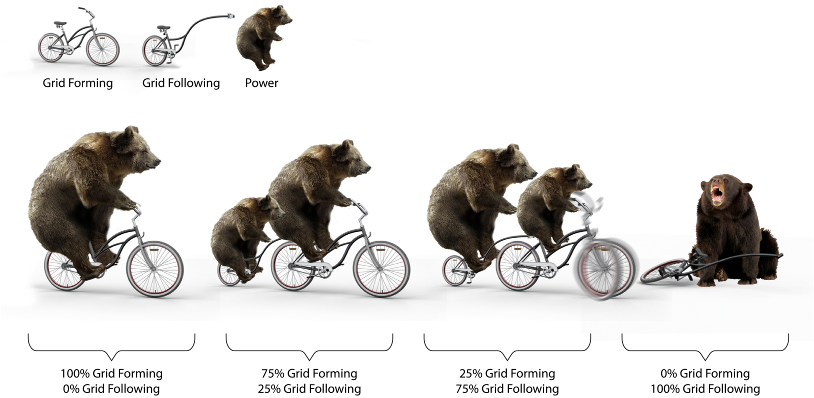
- agreement on fact: power systems **need XXX% of grid-forming sources**
- many services can be provided both in grid-forming / -following mode
- previous definitions are **compromise** found in MIGRATE project, but we also came up with frequency-domain characterizations "sensitivity to grid frequency"

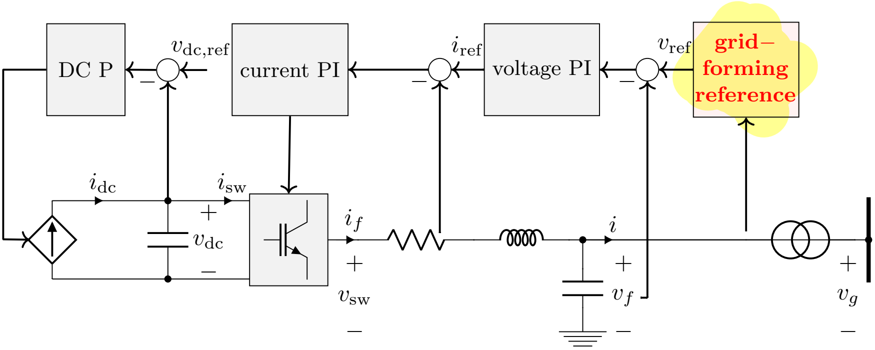


Fact: need XXX % grid-forming converters

figure taken from: *"Grid-Following Inverters and Synchronous Condensers"* by NREL

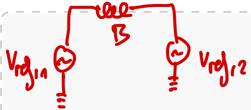


Grid-forming control "typically" enters as reference behavior in control architecture



What if the reference is droop behavior ?

(covered on the board)



(0) line is in steady state

(1) interconnection is lossless

(2) every converter can be modeled by its voltage reference dynamics

← perfect tracking of voltage/current

← do not encounter any state constraints

(3) neglect voltage amplitude $\|v_i\| = 1$

frequency imposed at converter i:

droop: $$\boxed{\omega_i = \omega_{ref} - K_i (P_i - P_{ref,i})}$$

with $$\omega_1 = \dot{\Theta}_1 = \omega_{ref} - k_1 (P_1 - P_{ref}) =$$

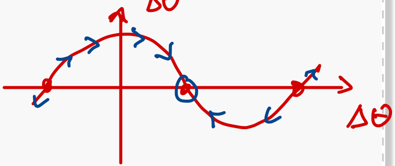
$$= \omega_{ref} - k_1 (B \sin(\Theta_1 - \Theta_2) - P_{ref,1})$$

What if the reference is droop behavior ?

(covered on the board)

difference coordinate: $\Delta\theta = \theta_1 - \theta_2$

$$\Delta\dot{\theta} = \omega_{ref} - k_1 B \sin(\theta_1 - \theta_2) - k_1 P_{1,ref}$$
$$- \omega_{ref} + k_2 B \sin(\theta_2 - \theta_1) - k_2 P_{2,ref}$$
$$= - \text{const.} \sin(\Delta\theta) + \text{const.}$$

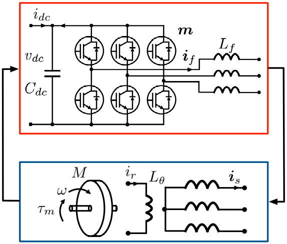


⇝ "almost globally stable"

⇝ θ_1 and θ_2 synchronize

Conventional reference behaviors

virtual synchronous machine

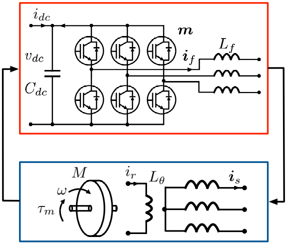


- **reference** = machine (order 3,. . . ,12)

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

Conventional reference behaviors

virtual synchronous machine



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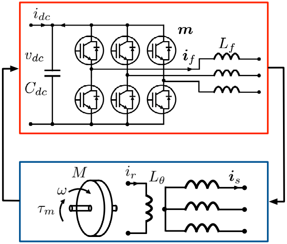
→ **poor fit**: converter ≠ flywheel
  - good small-signal but **poor post-fault performance** (reference not realizable)
  - **over-parametrized** & ignores **limits**

Conventional reference behaviors

virtual synchronous machine



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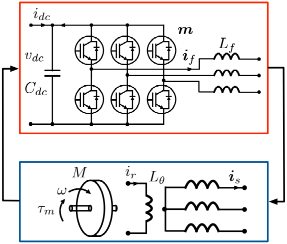
→ **emulate only "useful" dynamics**

Conventional reference behaviors

virtual synchronous machine



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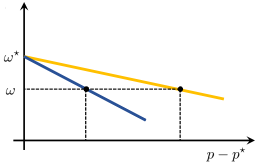
droop / power-synchronization



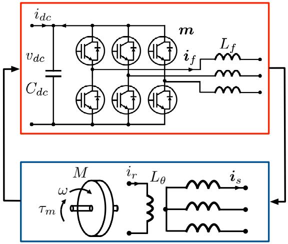
- **direct control** of frequency & voltage via (p, ω) & $(q, \|v\|)$ droop

$$\omega - \omega^\star \;\propto\; p - p^\star$$

$$\frac{d}{dt}\|v\| = -c_1(\|v\| - v^\star) - c_2(q - q^\star)$$

Conventional reference behaviors

virtual synchronous machine



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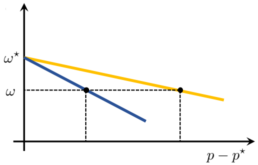

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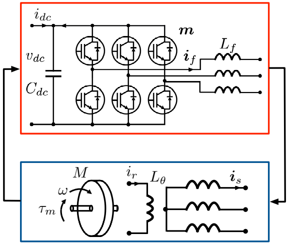
→ **decoupling ≠ true** in transients
  - → **good small-signal but poor large signal** (narrow region of attraction)
  - → main reason: **two linear SISO loops for MIMO nonlinear system**

Conventional reference behaviors

virtual synchronous machine



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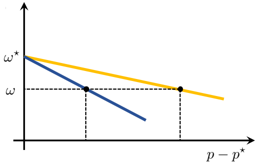

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→ **need "nonlinear & MIMO" droop**

Initial conditions for further reading

debated topic *"put the new system in the old shoes ?"* ⟶ make up your own mind

Virtual synchronous generators: A survey and new perspectives

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ABSTRACT

In comparison of the conventional bulk power plants, in which the synchronous machines dominate, the distributed generator (DG) units have either very small or no rotating mass and damping property. With growing the penetration level of DGs, the impact of low inertia and damping effect on the grid stability and dynamic performance increases. A solution towards stability improvement of such a grid is to provide virtual inertia by virtual synchronous generators (VSGs) that can be established by using short term energy storage together with a power inverter and a proper control mechanism.

The present paper reviews the fundamentals and main concept of VSGs, and their role to support the power grid control. Then, a VSG-based frequency control scheme is addressed, and the paper is focused on the poetical role of VSGs in the grid frequency regulation task. The most important VSG topologies with a survey on the recent works/achievements are presented. Finally, the relevant key issues, main technical challenges, further research needs and new perspectives are emphasized.

Comprehensive assessment of virtual synchronous machine based voltage source converter controllers

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Abstract: The substantial potential for the integration of renewable energy into power systems using power electronics converters might result in stability issues because of a lack of inertia. For this reason, this study introduces the concept of a virtual synchronous machine (VSM) control algorithm that emulates the properties of traditional synchronous machines. The literature includes references to several differently structured control algorithms. However, synchronous machine inertia and damping characteristics must be mimicked, which makes the cost and simplicity of implementation important from an economic perspective. This study presents a comprehensive comparison of VSM control algorithms. The most significant factor investigated in the work presented in this study is the viability of VSM algorithms during the kind of abnormal operation that might raise instability issues with respect to practical discrete time operation. The test system used in this study, which was simulated in a PSCAD/EMTDC environment, consisted of simulated voltage source converters based on a fully detailed switching model with two AC voltage levels. The results indicate a significant outcome that can facilitate a determination of the most effective VSM control algorithm.

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

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Kuramoto model
Distributed control

ABSTRACT

Motivated by the recent and growing interest in smart grid technology, we study the operation of DC/AC inverters in an inductive microgrid. We show that a network of loads and DC/AC inverters equipped with power-frequency droop controllers can be cast as a Kuramoto model of phase-coupled oscillators. This novel description, together with results from the theory of coupled oscillators, allows us to characterize the behavior of the network of inverters and loads. Specifically, we provide a necessary and sufficient condition for the existence of a synchronized solution that is unique and locally exponentially stable. We present a selection of controller gains leading to a desirable sharing of power among the inverters, and specify the set of loads which can be serviced without violating given actuation constraints. Moreover, we propose a distributed integral controller based on averaging algorithms, which dynamically regulates the system frequency in the presence of a time-varying load. Remarkably, this distributed-averaging integral controller has the additional property that it preserves the power sharing properties of the primary droop controller. Our results hold for any acyclic network topology, and hold without assumptions on identical line admittances or voltage magnitudes.

IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 58, NO. 4, APRIL 2011 1259

Synchronverters: Inverters That Mimic Synchronous Generators

Qing-Chang Zhong, *Senior Member, IEEE*, and George Weiss

Abstract—**In this paper, the idea of operating an inverter to mimic a synchronous generator (SG) is motivated and developed. We call the inverters that are operated in this way synchronverters. Using synchronverters, the well-established theory/algorithms used to control SGs can still be used in power systems where a significant proportion of the generating capacity is inverter-based. We describe the dynamics, implementation, and operation of synchronverters. The real and reactive power delivered by synchronverters connected in parallel and operated as generators can be automatically shared using the well-known frequency- and voltage-drooping mechanisms. Synchronverters can be easily operated also in island mode, and hence, they provide an ideal solution for microgrids or smart grids. Both simulation and experimental results are given to verify the idea.**

called inverters, to interface with the public-utility grid. For example, wind turbines are most effective if free to generate at variable frequency, and so, they require conversion from variable frequency ac to dc to ac; small gas-turbines with direct-drive generators operate at high frequency and also require ac to dc to ac conversion; photovoltaic arrays require dc–ac conversion. This means that more and more inverters will be connected to the grid and will eventually dominate power generation.

The current paradigm in the control of wind- or solar-power generators is to extract the maximum power from the power source and inject them all into the power grid (see, for example,

Control System Tuning and Stability Analysis of Virtual Synchronous Machines

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7495 Trondheim, Norway

Abstract—**Virtual Synchronous Machines (VSMs) have been introduced as a control concept for emulating the behavior of traditional synchronous machines with power electronic converters. This paper analyses a VSM control scheme where an outer loop for inertia emulation provides references for two cascaded voltage**

as well as stand-alone mode, and can ensure load sharing in the same way as the droop-based controls for UPS systems and microgrids [9]-[12]. Moreover, a VSM inherently includes the function of inertia emulation, which is expected to be important in future power systems with limited physical inertia [4], [6].

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Conditions for stability of droop-controlled inverter-based microgrids☆

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Smart grid applications
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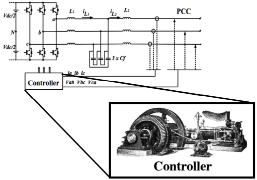
Port-Hamiltonian systems
Power sharing

ABSTRACT

We consider the problem of stability analysis for droop-controlled inverter-based microgrids with meshed topologies. The inverter models include variable frequencies as well as voltage amplitudes. Conditions on the tuning gains and setpoints for frequency and voltage stability, together with desired active power sharing, are derived in the paper. First, we prove that for all practical choices of these parameters global boundedness of trajectories is ensured. Subsequently, assuming the microgrid is lossless, a port-Hamiltonian description is derived, from which sufficient conditions for stability are given. Finally, we propose for generic lossy microgrids a design criterion for the controller gains and setpoints such that a desired steady-state active power distribution is achieved. The analysis is validated via simulation on a microgrid based on the CIGRE (Conseil International des Grands Réseaux Electriques) benchmark medium voltage distribution network.



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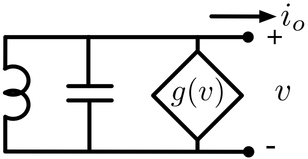
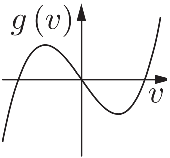
Grid-Forming Converters: Control Approaches, Grid-Synchronization, and Future Trends—A Review

ROBERTO ROSSO[1] (Student Member, IEEE), XIONGFEI WANG[2] (Senior Member, IEEE), MARCO LISERRE[3] (Fellow, IEEE), XIAONAN LU[4] (Member, IEEE), AND SOENKE ENGELKEN[5] (Senior Member, IEEE)

Modern reference behaviors: VOC family

nonlinear & open limit cycle oscillator as reference model





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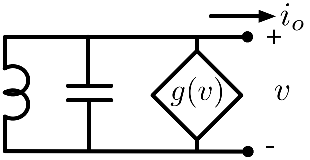

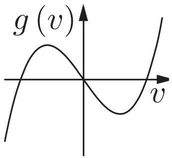

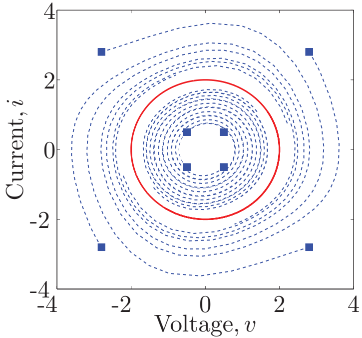

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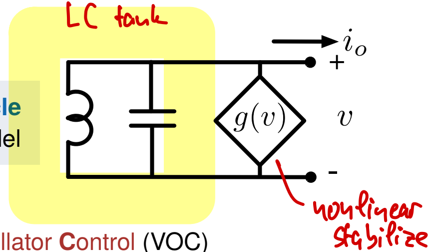
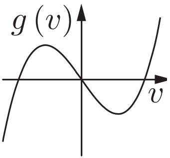




nonlinear & open limit cycle oscillator as reference model

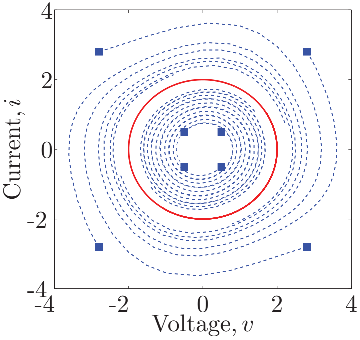
- early works on **V**irtual **O**scillator **C**ontrol (VOC)

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

$\rightarrow$ **almost global synchronization** & **local droop**

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

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



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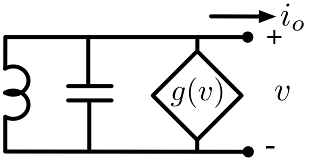

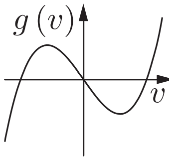

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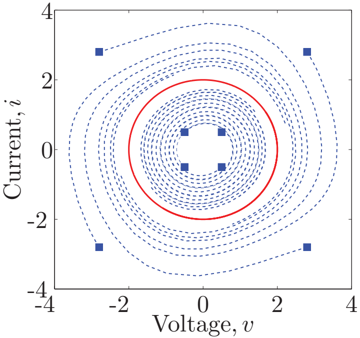
→ **almost global synchronization** & **local droop**

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

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

→ **dispatchable** virtual oscillator control

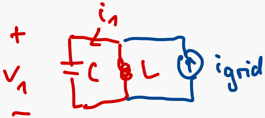
[Colombino, Groß, Brouillon, & Dörfler, '17, '18,'19],
[Subotic, Gross, Colombino, & Dörfler,'19]



Synchronization of virtual oscillators

(covered on the board)

LC tank = linear oscillator connected to a grid



$$\left.\begin{aligned} \frac{d}{dt} L i_1 &= v_1 \\ \frac{d}{dt} C v_1 &= -i_1 - i_{grid} \end{aligned}\right\} \quad \ddot{v}_1 = -\frac{1}{LC} v_1 - \frac{1}{C}\frac{d}{dt} i_{grid}$$

$$\rightsquigarrow \quad v_1(t) \sim \sin\left(\frac{1}{\sqrt{LC}}\, t\right)$$

Couple two LC tanks with a resistive wire: $i_{grid} = \frac{1}{R}(v_1 - v_2)$

$$\begin{aligned} \ddot{v}_1 &= -\frac{1}{LC} v_1 - \frac{1}{RC}(\dot{v}_1 - \dot{v}_2) \\ \ddot{v}_2 &= -\frac{1}{LC} v_2 - \frac{1}{RC}(\dot{v}_2 - \dot{v}_1) \end{aligned}$$

Coordinate change: $\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \to \begin{bmatrix} \Delta v \\ \tilde{v} \end{bmatrix} = \begin{bmatrix} v_1 - v_2 \\ v_1 + v_2 \end{bmatrix}$

<u>difference coordinate:</u>

$$\boxed{\Delta\ddot{v} = -\frac{1}{LC}\Delta v - \frac{1}{RC}\Delta\dot{v}} \quad \text{stable}$$

$\rightsquigarrow \Delta v \to 0$ "synchronize"

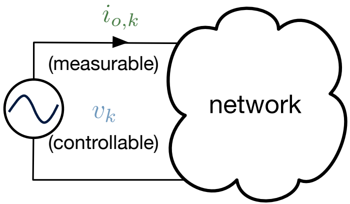
<u>average coordinate:</u>

$$\ddot{\tilde{v}} = -\frac{1}{LC}\tilde{v} \quad \rightsquigarrow \quad \tilde{v}(t) \sim \sin\left(1/\sqrt{LC}\, t\right)$$

$\rightsquigarrow$ synchronization to harmonic oscillation

improvement of original ad hoc
virtual oscillator control (VOC)

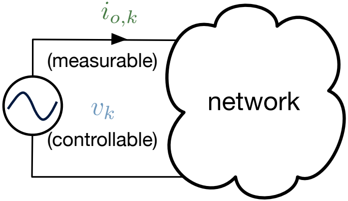
Model & control objectives (assumptions easy to generalize)



simplified multi-converter system model

- converter = **terminal voltage** $v_k \in \mathbb{R}^2$

Model & control objectives (assumptions easy to generalize)



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

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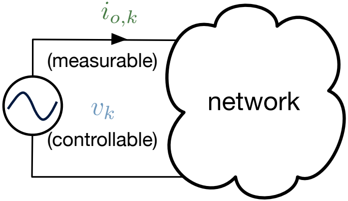

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- **homogeneous lines** with $\kappa = \frac{\ell_{jk}}{r_{jk}}$ constant

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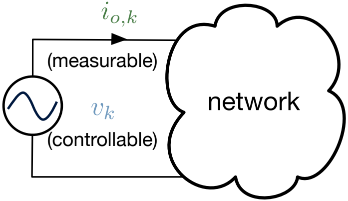

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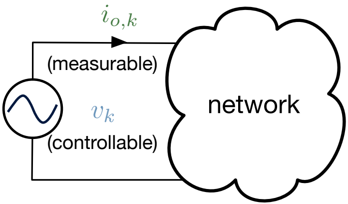
desired steady-state behavior

Model & control objectives (assumptions easy to generalize)



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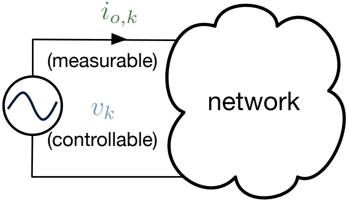
- **homogeneous lines** with $\kappa = \frac{\ell_{jk}}{r_{jk}}$ constant

desired steady-state behavior

- nominal **synchronous frequency**

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

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 simplicity)

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

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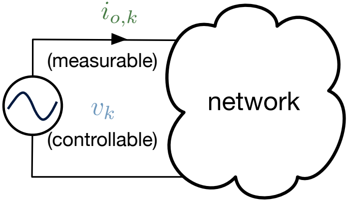

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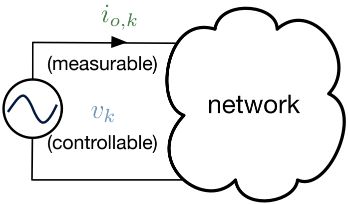
$$\|v_k\| = v^\star \qquad V \times \bar{I}$$

- active & reactive **power injection**

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

Model & control objectives (assumptions easy to generalize)



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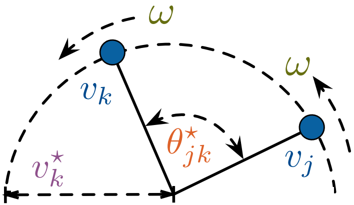
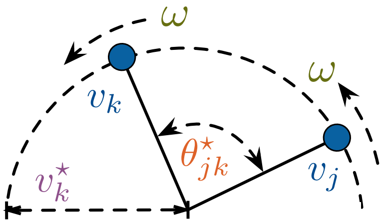
⇔ relative **angles**: $v_j = \begin{bmatrix} \cos(\theta_{jk}^\star) & -\sin(\theta_{jk}^\star) \\ \sin(\theta_{jk}^\star) & \cos(\theta_{jk}^\star) \end{bmatrix} v_k$



Colorful idea: closed-loop target dynamics



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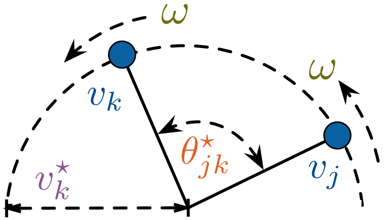

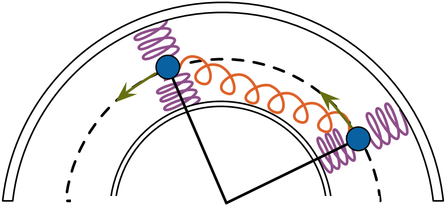

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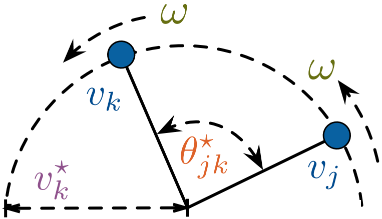

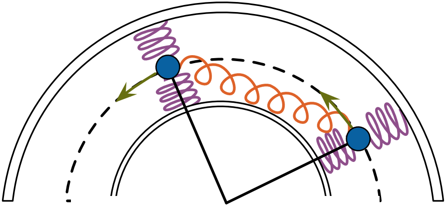

$$\frac{d}{dt}\boldsymbol{v_k} = \underbrace{\begin{bmatrix}0 & -\omega\\ \omega & 0\end{bmatrix}\boldsymbol{v_k}}_{\text{rotation at } \omega} + \underbrace{c_1\cdot\left(\|v_k\|^{\star 2} - \|\boldsymbol{v}_k\|^2\right)\boldsymbol{v}_k}_{\text{amplitude regulation to } v_k^\star}$$

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

$v_j = R(\theta_{jk}) \cdot v_k$

Decentralized implementation of dynamics

$$\underbrace{\sum_j w_{jk}(v_j - R(\theta^\star_{jk})v_k)}$$

need to know w_{jk}, v_j, v_k and $\theta^\star_{jk}$

Decentralized implementation of dynamics

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

$= -i$

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

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

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

$$p^\star_k = {v^\star}^2 \sum_j \frac{r_{jk}(1-\cos(\theta^\star_{jk})) - \omega_0 \ell_{jk} \sin(\theta^\star_{jk})}{r_{jk}^2 + \omega_0^2 \ell_{jk}^2}$$

$$q^\star_k = -{v^\star}^2 \sum_j \frac{\omega_0 \ell_{jk}(1-\cos(\theta^\star_{jk})) + r_{jk} \sin(\theta^\star_{jk})}{r_{jk}^2 + \omega_0^2 \ell_{jk}^2}$$

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

Properties of virtual oscillator control

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

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

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

$$\frac{d}{dt}\theta_k = \omega_0 + c_1\left(\frac{p_k^{\star}}{{v^{\star}}^2} - \frac{p_k}{\|v_k\|^2}\right)$$

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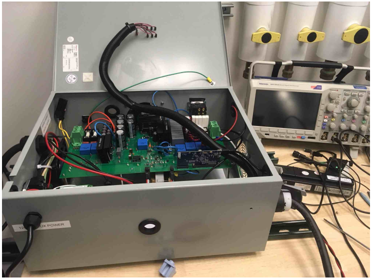
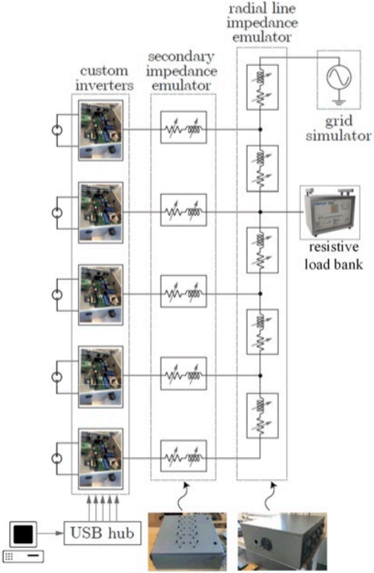
3. **almost global asymptotic stability** if

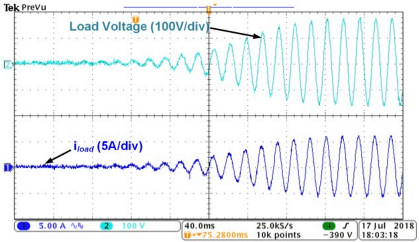
- **power transfer** “small” compared to **network connectivity**
- **amplitude control** “slower” than **synchronization control** $c_2 > c_1$

Experimental setup @ NREL

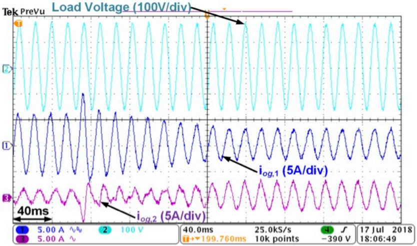




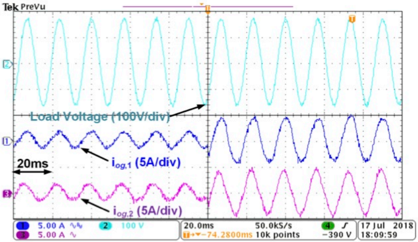
Experimental validation



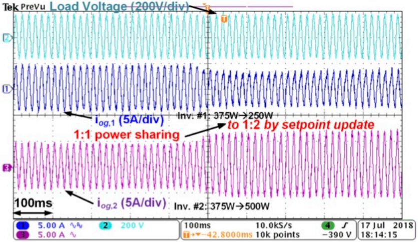
black start of inverter #1 under 500 W load (making use of almost global stability)



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

Initial conditions for further reading

Global Phase and Magnitude Synchronization of Coupled Oscillators With Application to the Control of Grid-Forming Power Inverters

Marcello Colombino, Dominic Groß, *Member, IEEE*, Jean-Sébastien Brouillon, and Florian Dörfler, *Member, IEEE*

***Abstract*—In this paper, we explore a new approach to synchronization of coupled oscillators. In contrast to the celebrated Kuramoto model, we do not work in polar coordinates and do not consider oscillations of fixed magnitude. We propose a synchronizing feedback based on relative state information and local measurements that induces consensus-like dynamics. We show that, under a mild stability condition, the combination of the synchronizing feedback with a decentralized magnitude control law renders the oscillators' almost globally asymptotically stable with respect to set points for the phase shift, frequency, and magnitude. We apply these result to rigorously solve an**

distribution grid may operate without conventional bulk generation by synchronous machines. In either case, the power grid faces great challenges due to the loss of the machines' rotational inertia and the loss of self-synchronization dynamics inherent to synchronous machines.

The prevalent approaches to controlling inverters in the future grid are based on mimicking the physical characteristics and controls of synchronous machines [1]–[3]. On the one hand, this approach is appealing because it results in a well-studied closed-loop behavior compatible with the legacy power system.

The Effect of Transmission-Line Dynamics on Grid-Forming Dispatchable Virtual Oscillator Control

Dominic Groß, *Member, IEEE*, Marcello Colombino, Jean-Sébastien Brouillon, and Florian Dörfler, *Member, IEEE*

***Abstract*—In this paper, we analyze the effect of transmission line dynamics on grid-forming control for inverter-based ac power systems. In particular, we investigate a dispatchable virtual oscillator control (dVOC) strategy that was recently proposed in the literature. When the dynamics of the transmission lines are neglected, that is, if an algebraic model of the transmission network is used, dVOC ensures almost global asymptotic stability of a network of ac power inverters with respect to a prespecified solution of the ac power-flow equations. While this approximation is typically justified for conventional power systems, the electromagnetic transients of the transmission lines can com-**

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$\longrightarrow$ dVOC $=$ **complex droop**:

$$\boxed{\tilde{\omega} - \tilde{\omega}^\star \sim \tilde{s} - \tilde{s}^\star}$$

$\tilde{\omega}$ & $\tilde{s}$ are *complex* frequency & power

Initial conditions for further reading

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Complex-Frequency Synchronization of Converter-Based Power Systems

Xiuqiang He, *Member, IEEE,* Verena Häberle, *Student Member, IEEE,* and Florian Dörfler, *Senior Member, IEEE*

***Abstract*—In this paper, we study phase-amplitude multivariable dynamics in converter-based power systems from a complex-frequency perspective. Complex frequency represents the rate of change of voltage amplitude and phase angle by its real and imaginary parts, respectively. This emerging notion is of significance as it accommodates the multivariable characteristics of power networks where active and reactive power are inherently coupled with both voltage amplitude and phase. We propose the notion of complex-frequency synchronization to study the phase-amplitude multivariable stability issue in a power system with dispatchable virtual oscillator-controlled (dVOC) converters. To achieve this, we separate the system into linear fast dynamics and approximately linear slow dynamics. The linearity property makes it tractable to analyze fast complex-frequency synchro-**

Power systems increasingly utilize power converters due to the unprecedented development of renewable energy integration. The loss of synchronism under grid disturbances has occurred in renewable power plants, leading to large-scale generation interruptions [5]. Such synchronization stability issues become increasingly challenging due to heterogeneous network characteristics and various converter control strategies. On the network side, P/θ and Q/V dynamics become tightly coupled, especially in distribution networks (with low X/R ratios) [6], which are increasingly penetrated by distributed energy resources. The sensitivity of load consumption to voltage variations also contributes to this coupling. On the converter-

The Effect of Transmission-Line Dynamics on Grid-Forming Dispatchable Virtual Oscillator Control

Dominic Groß, *Member, IEEE*, Marcello Colombino, Jean-Sébastien Brouillon, and Florian Dörfler, *Member, IEEE*

***Abstract*—In this paper, we analyze the effect of transmission line dynamics on grid-forming control for inverter-based ac power systems. In particular, we investigate a dispatchable virtual oscillator control (dVOC) strategy that was recently proposed in the literature. When the dynamics of the transmission lines are neglected, that is, if an algebraic model of the transmission network is used, dVOC ensures almost global asymptotic stability of a network of ac power inverters with respect to a prespecified solution of the ac power-flow equations. While this approximation is typically justified for conventional power systems, the electromagnetic transients of the transmission lines can com-**

inverter is not limited to power tracking, but acts as a controlled voltage source that can change its power output (thanks to storage or curtailment), and is controlled to contribute to the stability of the grid. Most of the common approaches of grid-forming control focus on droop control [1], [2]. Other popular approaches are based on mimicking the physical characteristics and controls of synchronous machines [3], [4] or controlling inverters to behave like virtual Liénard-type oscillators [5]–[7]. While strategies based on machine-emulation are compatible with the legacy power system, they use a system (the inverter)

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Quantitative Stability Conditions for Grid-Forming Converters With Complex Droop Control

Xiuqiang He, *Member, IEEE*, Linbin Huang, *Member, IEEE*, Irina Subotić, Verena Häberle, *Graduate Student Member, IEEE*, and Florian Dörfler, *Senior Member, IEEE*

***Abstract*—In this article, we analytically study the transient stability of grid-connected converters with grid-forming complex droop control, also known as dispatchable virtual oscillator control. We prove theoretically that complex droop control, as a state-of-the-art grid-forming control, always possesses steady-state equilibria, whereas classical droop control does not. We provide quantitative conditions for complex droop control maintaining *transient stability* (global asymptotic stability) under grid disturbances, which is beyond the well-established local (nonglobal) stability for classical droop control. For the *transient instability* of complex droop control, we reveal that the unstable trajectories are bounded, manifesting as limit cycle oscillations. Moreover, we extend our stability results from *second-order* grid-forming control dynamics to *full-order* system dynamics that additionally encompass both circuit electromagnetic transients and inner-loop dynamics. Our theoretical results contribute an insightful understanding of the transient stability and instability of complex droop control and offer practical guidelines for parameter tuning and stability guarantees.**

TABLE I
PAST STUDIES ON STABILITY OF TYPICAL GFM CONTROLS

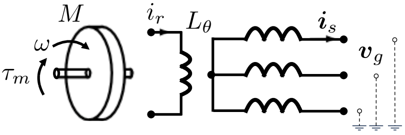
Ref.	Year	Type	Assumption	Method	Result	Publ.[1]
(a) Elementary GFM controls						
[4]	2012	1st-order Kuramoto model	Volt. fixed, network inductive	Linearization	Local	Ctrl.
[5]	2012	2nd-order Kuramoto model	Volt. fixed	Singular perturbation, contraction	Local	Ctrl.
[6]	2013	p/f droop in structure-preserving network	Volt. fixed, network inductive	Graph-theoretic methods, linearization	Local	PS
[7]	2014	p/f and q/v droop	Network inductive	Lyapunov-like analysis	Local and global	Ctrl.
[8]	2019	p/f droop	Volt. fixed, network inductive	Phase portrait	Global	PE
[9]	2019	Current-limited	Volt. fixed, network	Power-angle curve analysis	ROA	PS

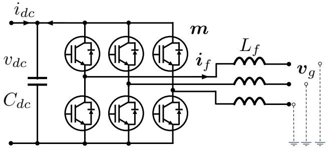
$\longrightarrow$ dVOC $=$ **complex droop**:

$$\tilde{\omega} - \tilde{\omega}^\star \sim \tilde{s} - \tilde{s}^\star$$

$\tilde{\omega}$ & $\tilde{s}$ are *complex* frequency & power

Duality & matching of synchronous machine





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

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

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

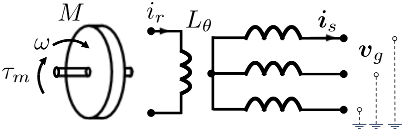
$$C_{\mathsf{dc}}\frac{\mathrm{d}v_{\mathsf{dc}}}{\mathrm{d}t} = -G_{\mathsf{dc}}v_{\mathsf{dc}} + i_{\mathsf{dc}} + \boldsymbol{m}^\top \boldsymbol{i}_f$$

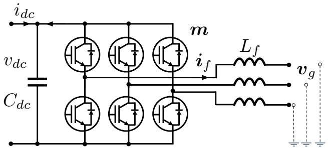
$$L_f\frac{\mathrm{d}\boldsymbol{i}_f}{\mathrm{d}t} = -R_f\boldsymbol{i}_f + \boldsymbol{v}_g - \boldsymbol{m}\, v_{\mathsf{dc}}$$

$m \in [-1/2, +1/2]^2$

$m = m_{ampl} \cdot \begin{bmatrix} -\sin(\delta) \\ \cos(\delta) \end{bmatrix}$

Duality & matching of synchronous machine





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

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

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

$$\frac{\mathrm{d}\delta}{\mathrm{d}t} = m_\mathrm{freq} = v_{dc}$$

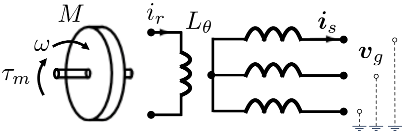
$$C_\mathrm{dc}\frac{\mathrm{d}v_\mathrm{dc}}{\mathrm{d}t} = -G_\mathrm{dc} v_\mathrm{dc} + i_\mathrm{dc} + m_\mathrm{ampl} \begin{bmatrix} -\sin\delta \\ \cos\delta \end{bmatrix}^\top \boldsymbol{i}_f$$

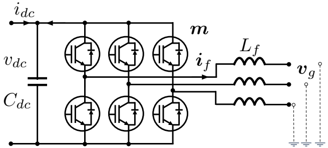
$$L_f \frac{\mathrm{d}\boldsymbol{i}_f}{\mathrm{d}t} = -R_f \boldsymbol{i}_f + \boldsymbol{v}_g - m_\mathrm{ampl} \begin{bmatrix} -\sin\delta \\ \cos\delta \end{bmatrix} v_\mathrm{dc}$$

1. modulation in polar coordinates:

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

Duality & matching of synchronous machine





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

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

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

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

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

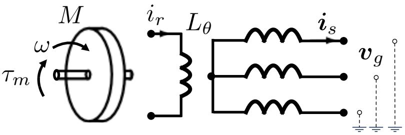
$$L_f\frac{\mathrm{d}\boldsymbol{i}_f}{\mathrm{d}t} = -R_f \boldsymbol{i}_f + \boldsymbol{v}_g - m_\mathrm{ampl} \begin{bmatrix} -\sin\delta \\ \cos\delta \end{bmatrix} v_\mathrm{dc}$$

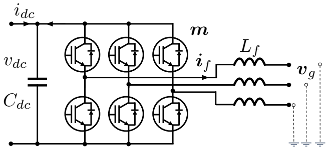
1. modulation in polar coordinates:

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

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

Duality & matching of synchronous machine





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

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

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

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

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

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

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 $\eta = \frac{\omega_{\mathrm{ref}}}{v_{\mathrm{dc,ref}}}$

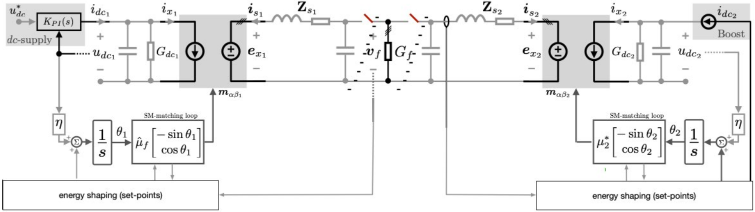
$\rightarrow$ **duality**: $C_{\mathrm{dc}} \sim M$ is equivalent inertia

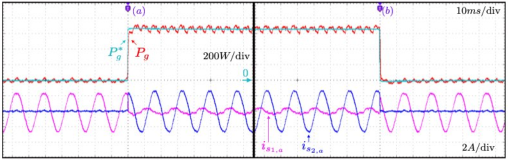
structural similarities:

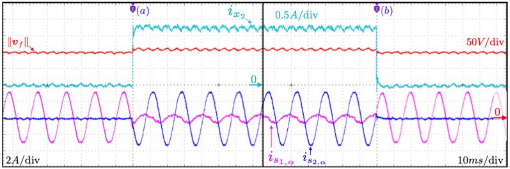
- states: $\theta = \delta$, $\omega = \eta v_{\mathrm{dc}}$, $\boldsymbol{i}_s = \boldsymbol{i}_f$
- control: $u_{\mathrm{ampl}} = L_m i_r$, $i_{\mathrm{dc}}/\eta = \tau_m$

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

Experimental validation (concept often replicated)







Details & initial conditions for further reading

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The Electronic Realization of Synchronous Machines: Model Matching, Angle Tracking, and Energy Shaping Techniques

Catalin Arghir and Florian Dörfler

Abstract—**In this article, we investigate grid-forming and grid-following control strategies starting from a nonlinear state-space modeling viewpoint. An electronic synchronous machine is an inverter whose integral of the dc-bus measurement generates the angle of the instantaneous modulation vector. We show how this minimal augmentation constitutes an exact physical realization**

running in the feedback path, which settle at the appropriate steady state. However, the large number of states of the inner loops makes the analysis of multiple converters difficult [4], motivating the study of more direct control approaches, [5], [6].

With the growing complexity of the power system at large

Grid-forming control for power converters based on matching of synchronous machines

Catalin Arghir *, Taouba Jouini, Florian Dörfler

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ABSTRACT

We consider the problem of grid-forming control of power converters in low-inertia power systems. Starting from an average-switch three-phase power converter model, we draw parallels to a synchronous machine (SM) model and propose a novel converter control strategy which dwells upon the main characteristic of a SM: the presence of an internal rotating magnetic field. In particular, we augment the converter system with a virtual oscillator whose frequency is driven by the DC-side voltage measurement and which sets the converter pulse-width-modulation signal, thereby achieving exact matching between the converter in closed-loop and the SM dynamics. We then provide a sufficient condition asserting existence, uniqueness, and global asymptotic stability of a shifted equilibrium, all in a rotating coordinate frame attached to the virtual oscillator angle. By actuating the DC-side input of the converter we are able to enforce this condition and provide additional inertia and damping. In this framework, we illustrate strict incremental passivity, droop, and power-sharing properties which are compatible with conventional power system operation requirements. We subsequently adopt disturbance-decoupling and droop techniques to design additional control loops that regulate the DC-side voltage, as well as AC-side frequency and amplitude, while in the end evaluating them with numerical experiments.

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Hybrid Angle Control and Almost Global Stability of Non-synchronous Hybrid AC/DC Power Grids

Ali Tayyebi and Florian Dörfler

Abstract—**This paper explores the stability of non-synchronous hybrid ac/dc power grids under the grid-forming hybrid angle control strategy. We formulate dynamical models for the ac grids and transmission lines, interlinking converters, and dc generations and interconnections. Next, we establish the existence and uniqueness of the closed-loop equilibria for the overall system. Subsequently, we demonstrate global attractivity of the equilibria, local asymptotic stability of the desired equilibrium point, and instability and zero-Lebesgue-measure region of attraction for other equilibria. The theoretic results are derived under mild, parametric, and unified stability/instability conditions. Finally, relying on the intermediate results, we conclude the almost global asymptotic stability of the hybrid ac/dc power grids with interlinking converters that are equipped with hybrid angle control. Last, we present several remarks on the practical and theoretical aspects of the problem under investigation.**

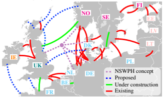


Fig. 1: The overview of the high voltage dc (HVDC) links and North Sea wind power hub (NSWPH) concept that connect the regional groups (RGs) in the Northern Europe and Baltic regions [1].

also applicable in a **dual-port setup** (HVDC, wind turbine, hybrid grid, . . .) à la

$$\dot{\theta} = c_1 \cdot (\text{dc imbalance}) + c_2 \cdot (\text{ac imbalance})$$

to map imbalances across dc/ac ports & assure simultaneous dc & ac grid-forming

Dual-port grid-forming control of MMCs and its applications to grids of grids

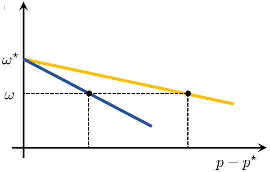
Dominic Groß, *Member, IEEE,* Enric Sánchez-Sánchez, *Member, IEEE,* Eduardo Prieto-Araujo, *Senior Member, IEEE,* and Oriol Gomis-Bellmunt, *Fellow, IEEE*

Abstract—**This work focuses on grid-forming (GFM) control of Interconnecting Power Converters (IPCs) that are used to interconnect multiple HVAC and HVDC subgrids to form a grid of grids. We introduce the concept of dual-port GFM control that leverages the ability of Modular Multilevel Converters (MMCs) to simultaneously form its AC and DC terminal voltage and present two dual-port GFM MMC controls. We provide analytical results and high-fidelity simulations that demonstrate that (i) dual-port GFM control is more resilient to contingencies (i.e., line and generator outages) than state-of-the-art single-port GFM control, and (ii) unlike single-port GFM control, dual-port GFM control does not require assigning grid-forming and grid-following (GFL) roles to the IPC terminals in grids of grids. Finally, we provide an in-depth discussion and comparison of single-port GFM control and the proposed dual-port GFM controls.**

grid-forming (GFM) strategies that form a stable AC voltage (i.e., magnitude and frequency) at the converter terminal. As a consequence of relying on a stable AC voltage, GFL control may fail due to voltage disturbances [4] or if insufficient GFM units (i.e., synchronous generators or GFM converters) are online to ensure frequency stability.

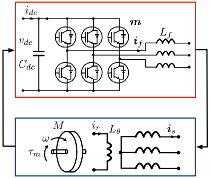
In contrast, GFM power converters can form a stable grid and are envisioned to be the cornerstone of future power systems. The prevalent approaches to GFM control are so-called droop-control [5], synchronous machine emulation [6], and (dispatchable) virtual oscillator control [7], [8]. All of the aforementioned controls form a stable AC voltage waveform and provide primary frequency control. However, they require comparison of grid-forming controllers

High-level comparison



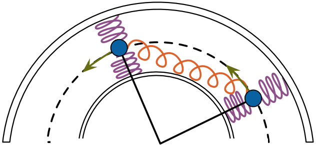
droop control

- **+** good performance near steady state
- **–** relies on decoupling & small attraction basin



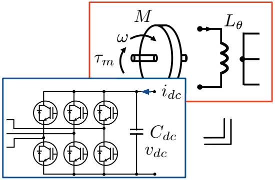
synchronous machine emulation

- **+** backward compatible in nominal case
- **–** not resilient under large disturbances



virtual oscillator control

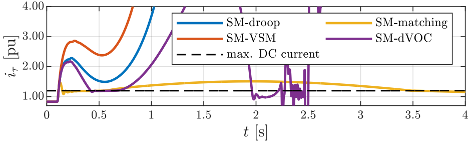
- **+** excellent large-signal behavior + local droop
- **–** voc, droop, & vsm need strong dc source

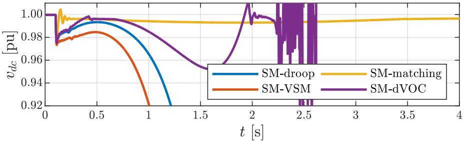


matching control & duality

- **+** simple & robust
- **–** slow ac performance

Detailed comparison study @AIT



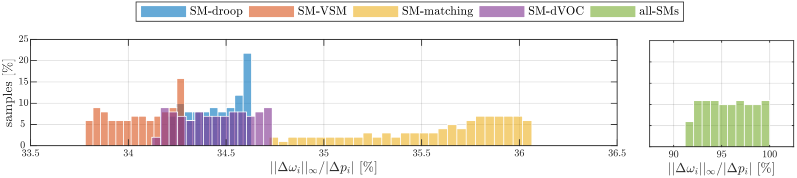


- **all perform well** nominally & under minor disturbances
- **relative resilience** :

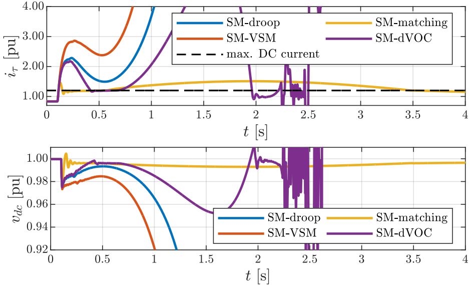
  matching > VOC > droop > virtual synchronous machine

Frequency Stability of Synchronous Machines and Grid-Forming Power Converters

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



Detailed comparison study @AIT



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

Frequency Stability of Synchronous Machines and Grid-Forming Power Converters

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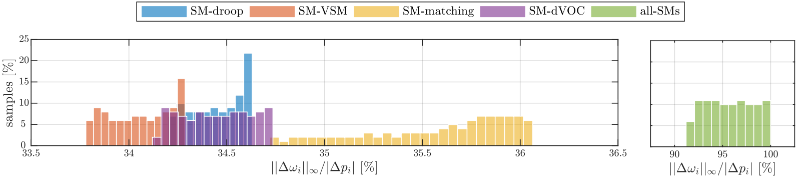
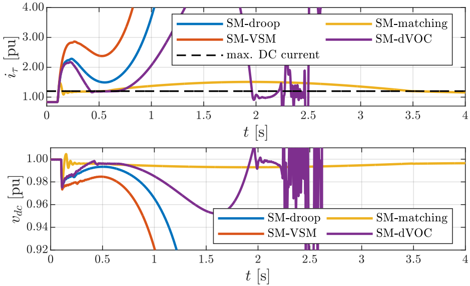


Detailed comparison study @AIT



Frequency Stability of Synchronous Machines and Grid-Forming Power Converters

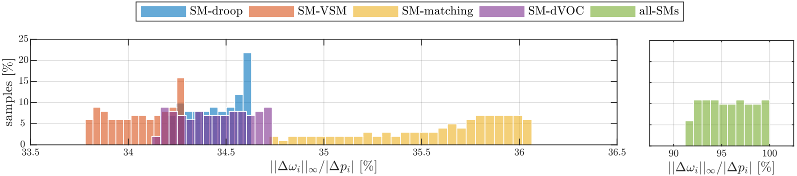
Ali Tayyebi, Dominic Groß, *Member, IEEE*, Adolfo Anta, Friederich Kupzog and Florian Dörfler, *Member, IEEE*

- **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



Detailed comparison(s) (stopped collecting references at mid 2020)

Comparison of Virtual Oscillator and Droop Controlled Islanded Three-Phase Microgrids

Zhan Shi, *Member, IEEE*, Jiacheng Li, *Student Member, IEEE*, Hendra I. Nurdin, *Senior Member, IEEE*, and John E. Fletcher, *Senior Member, IEEE*

Comparison of Virtual Oscillator and Droop Control

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Similarities between Virtual Oscillator Controlled and Droop Controlled Three-Phase Inverters

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Comparative Transient Stability Assessment of Droop and Dispatchable Virtual Oscillator Controlled Grid-Connected Inverters

Hui Yu, *Student Member, IEEE,* M A Awal, *Student Member, IEEE,* Hao Tu, *Student Member, IEEE,* Iqbal Husain, *Fellow, IEEE* and Srdjan Lukic, *Senior Member, IEEE,*

Frequency Stability of Synchronous Machines and Grid-Forming Power Converters

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

GRID-FORMING CONVERTERS – INEVITABILITY, CONTROL STRATEGIES AND CHALLENGES IN FUTURE GRIDS APPLICATION

Ali TAYYEBI
AIT and ETH Zürich – Austria

Florian DÖRFLER
ETH Zürich – Switzerland

Friederich KUPZOG
Austrian Institute of Technology – Austria

Comparison of Droop Control and Virtual Oscillator Control Realized by Andronov-Hopf Dynamics

Minghui Lu[*], Victor Purba[†], Sairaj Dhople[†], Brian Johnson[*]

Transient response comparison of virtual oscillator controlled and droop controlled three-phase inverters under load changes

Zhan Shi[1] ✉, Jiacheng Li[1], Hendra I. Nurdin[1], John E. Fletcher[1]
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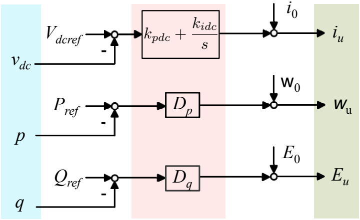
- **matching control** $\omega \sim v_{\mathrm{dc}}$ **is most robust** though with slow AC dynamics
- ...comparison suggests **multivariable control** (e.g., VOC + matching)

Abstract perspective on converter controls

① **droop** control = 3 decoupled **SISO** loops



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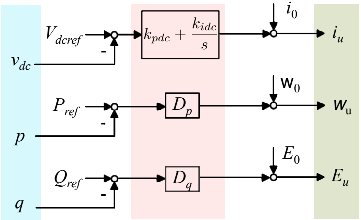
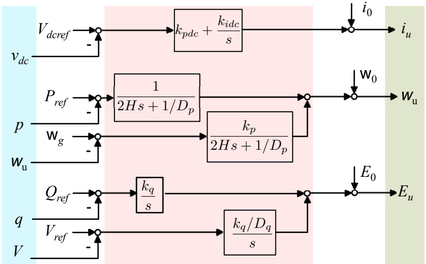


② **virtual machine** = droop + **filters** + . . .



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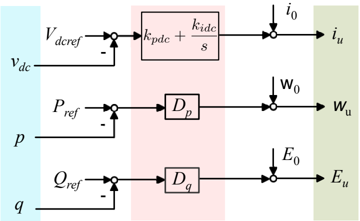
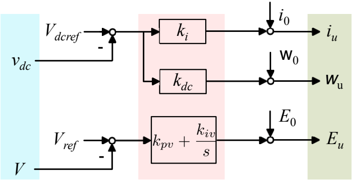


③ **matching** = **unconventional** coupling



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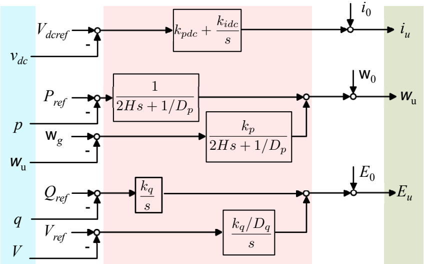

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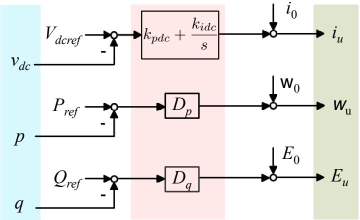

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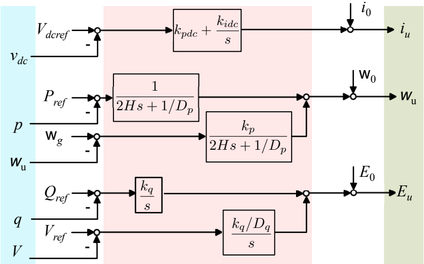

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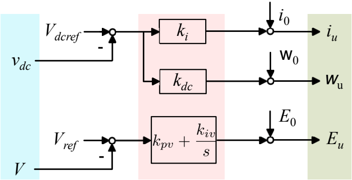

④ **nonlinear & coupled preprocessing** of control inputs: **virtual oscillator control**

$$\begin{bmatrix} p \\ q \\ \|v\| \end{bmatrix} \mapsto \begin{bmatrix} p/\|v\|^2 \\ q/\|v\|^2 \\ \|v\| \end{bmatrix} \mapsto \text{control loops} \mapsto u$$

or droop **adapting** to impedance angle φ

$$\begin{bmatrix} p \\ q \end{bmatrix} \mapsto \begin{bmatrix} \cos\varphi & \sin\varphi \\ -\sin\varphi & \cos\varphi \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \mapsto \text{control loops} \mapsto u$$

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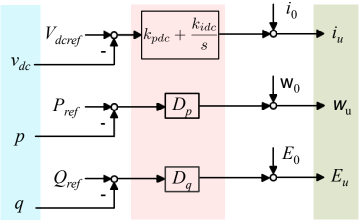

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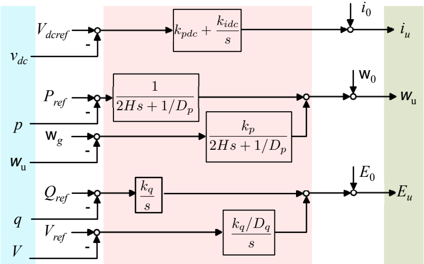

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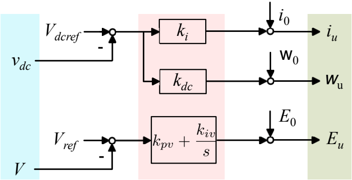

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$\Rightarrow$ seek **MIMO, dynamic, & nonlinear** control

Optimal multivariable grid-forming control

$$\begin{bmatrix} u_1 \\ \vdots \\ u_m \end{bmatrix} = \mathbb{K}(s) \begin{bmatrix} y_1 \\ \vdots \\ y_p \end{bmatrix}$$

- inputs: modulation, dc-power supply, & inner references
- outputs: (nonlinear) state tracking errors

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→ can **include all other controls** (e.g., droop or VOC) depending on I/O's

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- **forming / following mode** enforced by small-signal Bode characterization
- **linear stability** under interconnection

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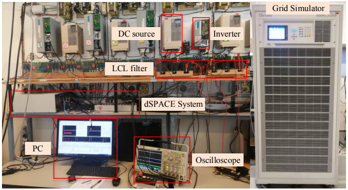

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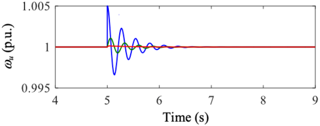

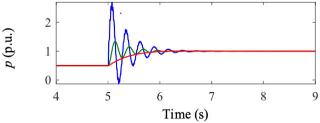

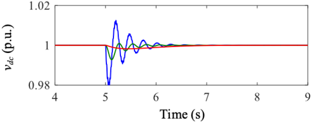

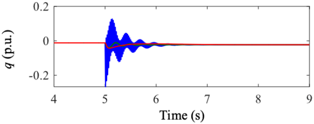

- droop control
- virtual synchronous machine emulation
- optimal & multivariable

Initial conditions for further reading

IEEE TRANSACTIONS ON SMART GRID, VOL. 13, NO. 4, JULY 2022 2873

Generalized Multivariable Grid-Forming Control Design for Power Converters

Meng Chen, *Member, IEEE*, Dao Zhou, *Senior Member, IEEE*, Ali Tayyebi, Eduardo Prieto-Araujo, *Senior Member, IEEE*, Florian Dörfler, *Senior Member, IEEE*, and Frede Blaabjerg, *Fellow, IEEE*

***Abstract*—The grid-forming converter is an important unit in the future power system with more inverter-interfaced generators. However, improving its performance is still a key challenge. This paper proposes a generalized architecture of the grid-forming converter from the view of multivariable feedback control. As a result, many of the existing popular control strategies, i.e., droop control, power synchronization control, virtual synchronous generator control, matching control, dispatchable virtual oscillator control, and their improved forms are unified into a multivariable feedback control transfer matrix working on several linear and nonlinear error signals. Meanwhile, unlike the traditional assumptions of decoupling between AC and DC control, active power and reactive power control, the proposed configuration simultaneously takes all of them into consideration, which therefore can provide better performance. As an example, a new multi-input-multi-output-based grid-forming (MIMO-GFM) control is proposed based on the generalized configuration. To cope with the multivariable feedback, an optimal and structured $\mathcal{H}_\infty$ synthesis is used to design the control parameters. At last, simulation and experimental results show superior performance and robustness of the proposed configuration and control.**

tasks of the smart grid is to enable a robust integration of various renewable energies and energy storage systems. As most of these are interfaced via power inverters, the control of power inverters plays a fundamental role to ensure the requirements of the smart grid on stable, flexible, and efficient power regulation [1]–[3].

As more inverter-interfaced generators (IIGs) are integrated into the smart grid, stability issues are becoming more pronounced due to the lack of inertia and poor regulation of the frequency and voltage. To cope with these challenges, grid-forming converters can establish the frequency and voltage by themselves without relying on the power grid. The synchronization among the grid-forming converters and with the power grid is based on the power balance rather than on a phase-locked loop (PLL) like in a traditional grid-following converter. Therefore, by proper power control, grid-forming converters are able to participate in the frequency and voltage regulation and then help to enlarge the penetration of the IIGs in the power system. On the

14280 IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 37, NO. 12, DECEMBER 2022

State Feedback Reshaping Control of Voltage Source Converter

Federico Cecati, *Member, IEEE*, Rongwu Zhu, *Member, IEEE*, Sante Pugliese, *Member, IEEE*, Marco Liserre, *Fellow, IEEE*, and Xiongfei Wang, *Senior Member, IEEE*

***Abstract*—Admittance reshaping is a widely used strategy to address the converters low-frequency stability issues in weak grid, caused by the PLL and its interaction with the dc and ac voltage controls. However, the asymmetric control of the *d*- and *q*-axis current references and the coupling between the converter ac and dc sides restricts the damping capability of single-input single-output feedbacks. This phenomenon gets even worse in the presence of nearby converters. This article extends the concept of admittance reshaping to multi-input multi-output control. A full state feedback is added to the current reference of the converter to increase the damping of the conventional multiloop control. A systematic offline algorithm is delegated to design the feedback, and a scalar coefficient is employed to activate/deactivate online the reshaping feedback, making the proposed solution user-friendly. The proposed control is analyzed both in time and frequency domains and tested in parallel-operation with other converters, and shows higher damping capability than conventional solutions and good robustness with respect to grid impedance and operating point variations. Experimental tests under ac and dc disturbances are conducted both in lab setup and in hardware-in-the-loop.**

$v_{cc} \in \mathbb{R}^2$	Auxiliary state variable of the current control.
$i_g \in \mathbb{R}^2$	Converter injected ac current.
$x \in \mathbb{R}^{11}$	State vector.
$u \in \mathbb{R}^2$	Reshaping control input vector.
$d \in \mathbb{R}^3$	Disturbance input vector.
$r \in \mathbb{R}^2$	Reference input vector.
$y \in \mathbb{R}^3$	Output vector.
$T(\delta) \in \mathbb{R}^{2\times2}$	Reference frame transformation matrix.
$\Omega \in \mathbb{R}^{2\times2}$	dq axes cross-coupling matrix.
$v_{dc}^* \in \mathbb{R}$	DC-link voltage voltage reference.
$v_g^* \in \mathbb{R}$	AC voltage voltage reference.
$i_g^* \in \mathbb{R}^2$	Current control reference.
$\omega_{cc} \in \mathbb{R}$	Bandwidth of the current loop in rad/s.
$C_{dc} \in \mathbb{R}$	DC-link capacitor.
$K_p \in \mathbb{R}$	Proportional gain of the current controller.
$K_i \in \mathbb{R}$	Integral gain of the current controller.
$K_{p,DC} \in \mathbb{R}$	Proportional gain of the dc voltage controller.

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Grid-Forming Hybrid Angle Control and Almost Global Stability of the DC–AC Power Converter

Ali Tayyebi, Adolfo Anta, and Florian Dörfler

***Abstract*—This article introduces a new grid-forming control for a grid-connected dc–ac power converter, termed hybrid angle control (HAC) that combines the dc-based matching control with a novel nonlinear angle feedback reminiscent of (though not identical to) classic droop control. The synthesis of HAC is inspired by the complementary benefits of the dc-based matching and ac-based grid-forming controls as well as ideas from direct angle control and nonlinear damping assignment. The proposed HAC is applied to a nonlinear converter model that is connected to an infinite bus or a center-of-inertia dynamic grid models. We provide parametric sufficient existence, uniqueness, stability, and boundedness conditions that are met by appropriate choice of control parameters. Next, we take into account the safety constraints of power converter, and synthesize a new current-limiting control that is compatible with HAC. Last, we present details on the practical implementation of HAC that are followed by a robustness analysis (which showcases a theory–practice gap), uncover the HAC droop behavior, derive a feedforward-like ac voltage and power control, and illustrate the behavior of the system with simulation case studies.**

whereby the converter features frequency and voltage control, black-start, and load-sharing capabilities.

Several grid-forming control techniques have been recently proposed. *Droop control* mimics the speed droop of synchronous generators (SG), controls the converter modulation angle proportional to the active power imbalance, and is widely recognized as the baseline solution [4]. As a natural extension of droop control, the emulation of SG dynamics and control led to *virtual synchronous machine* (VSM) strategies [5]. The recently proposed *matching* control exploits structural similarities of the converter and SG; and matches their dynamics by controlling the modulation angle according to the dc voltage [7]–[10]. Furthermore, *virtual oscillator control* (VOC) mimics the dynamical behavior of Liénard-type oscillators and *globally* synchronizes a converter-based network, [11]. Last, *dispatchable virtual oscillator control* (dVOC) is proposed that ensures *almost global* synchronization of a network of oscillator-controlled converters to prespecified set-points consistent with the power flow equations [12].

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On Power Control of Grid-Forming Converters: Modeling, Controllability, and Full-State Feedback Design

Meng Chen, *Member, IEEE*, Dao Zhou, *Senior Member, IEEE*, Ali Tayyebi, Eduardo Prieto-Araujo, *Senior Member, IEEE*, Florian Dörfler, *Senior Member, IEEE*, and Frede Blaabjerg, *Fellow, IEEE*

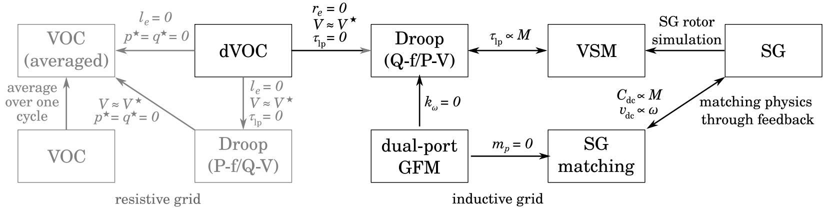
***Abstract*—The popular single-input single-output control structures and classic design methods (e.g., root locus analysis) for the power control of grid-forming converters have limitations in applying to different line characteristics and providing favorable performance. This paper studies the grid-forming converter power loops from the perspective of multi-input multi-output systems. First, the error dynamics associated with power control loops (error-based state-space model) are derived while taking into account the natural dynamical coupling terms of the power converter models. Thereafter, the controllability Gramian of the grid-forming converter power loops is studied. Last, a full-state feedback control design using only the local measurements is applied. By this way, the eigenvalues of the system can be arbitrarily placed in the timescale of power loops based on predefined time-domain specifications. A step-by-step construction and design procedure of the power control of grid-forming converters is also given. The analysis and proposed method are verified by experimental results and system-level simulation comparisons in Matlab/Simulink.**

converters is typically nested with multiple loops, e.g., inner cascaded voltage and current loops as well as the outer power loops. To simplify the analysis and design, the cascaded loops are usually designed with higher bandwidths than those of the power loops. As a result, the cascaded loops with the fast dynamics and the power loops with the slow dynamics can be studied separately [1].

In terms of the cascaded loops, the conventional structure is with double proportional-plus-integral (PI) controllers. In [2], an additional high-pass filter is added to the current feedback loop to obtain a faster voltage tracking. The sliding-mode control is used to completely replace the PI control for the cascaded loops in [3]. These strategies enhance the decoupling between the inner cascaded loops and the outer power loops.

As for the power controls, several strategies have been pro-

Often **research goes in circles** until we (hopefully) arrive at a bigger picture



Summary of Control Transfer Matrices Corresponding to Different Grid-forming Controllers

Feedback Signals $\boldsymbol{y}$	v_{dc}	p	ω_u	q	V	v_{dc}	p	ω_u	q	V	v_{dc}	p	ω_u	q	V
Transfer Matrix ϕ_{ij}	ϕ_{11}	ϕ_{12}	ϕ_{13}	ϕ_{14}	ϕ_{15}	ϕ_{21}	ϕ_{22}	ϕ_{23}	ϕ_{24}	ϕ_{25}	ϕ_{31}	ϕ_{32}	ϕ_{33}	ϕ_{34}	ϕ_{35}
droop-1 [2], [3]	PI	0	0	0	0	0	P	0	0	0	0	0	0	P	0
droop-2 [8]	PI	0	0	0	0	0	0	0	P	0	0	I	0	0	I
droop-3 [3], [30]	PI	0	0	0	0	0	IF	0	0	0	0	0	0	0	0
droop-4 [11]	PI	0	0	0	0	0	PD	0	0	0	0	0	0	P	0
droop-5 [4]	PI	0	0	0	0	0	P{IF×D}	0	0	0	0	0	0	P	0
PSC-1 [3]	PI	0	0	0	0	0	P	0	0	0	0	0	0	P	0
PSC-2 [12]	PI	0	0	0	0	0	IF×PD	0	0	0	0	0	0	I	0
PSC-3 [13]	PI	0	0	0	0	0	IF×PD	0	0	0	0	0	0	I	0
VSG-1 [22], [31]	PI	0	0	0	0	0	IF	0	0	0	0	0	0	0	IF
VSG-2 [21], [22], [29]	PI	0	0	0	0	0	IF	0	0	0	0	0	0	PI	PI
VSG-3 [17]	PI	0	0	0	0	0	IF	0	0	0	0	0	P	P	0
VSG-4 [32]	PI	0	0	0	0	0	IF	IF	0	0	0	0	0	P	0
VSG-5 [4], [21], [33]	PI	0	0	0	0	0	IF	IF	0	0	0	0	0	PI	PI
VSG-6 [16]	PI	0	0	0	0	0	IF	0	0	IF	0	0	0	I	I
VSG-7 [15]	PI	0	0	0	0	0	O×PD	0	0	0	0	0	0	I	I
VSG-8 [4]	PI	0	0	0	0	0	IF×PD	0	0	0	0	0	0	PI	PI
VSG-9 [19]	PI	0	0	0	0	IF×PD	IF×PD	0	0	0	0	0	0	P	0
VSG-10 [21]	PI	0	0	0	0	0	$IF_1\{IF_1 \times IF_2 \times D\}$	0	0	0	0	0	0	PI	PI
VSG-11 [23]	PI	0	0	0	0	0	O×PD{O×IF×PD×D}	0	0	0	0	0	0	I	I
VSG-12 [20], [21]	PI	0	0	0	0	0	$O \times PD_1\{O \times IF \times PD_2 \times D\}$	0	0	0	0	0	0	PI	PI
matching-1 [5]	P	0	0	0	0	P	0	0	0	0	0	0	0	0	PI
matching-2 [18]	0	0	0	0	0	P	0	0	0	0	P	0	0	0	0
Generated Inputs $\boldsymbol{u}$			i_u				ω_u						E_u		

Control of Low-Inertia Power Systems

Florian Dörfler[1] and Dominic Groß[2]

[1]Automatic Control Laboratory, ETH Zurich, Zurich, Switzerland, 8092; email: dorfler@ethz.ch
[2]Electrical and Computer Engineering, University of Wisconsin-Madison, Madison, United States, WI 53706; email: dominic.gross@wisc.edu

When you actually *implement* grid-forming controls, you realize that you need …

- ✓ **performant inner control loops**: highly tuned and/or MIMO versions
- ✓ **low-pass filters**: to avoid algebraic loops, filter measurements, and/or control bandwidth of controls (e.g., to ensure time-scale separation)

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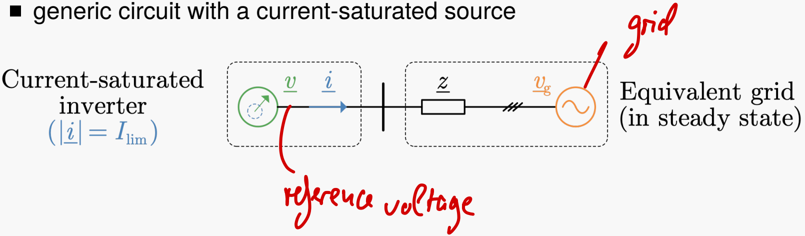
$\longrightarrow$ *over-educated solutions*: MPC, projected dynamics, … $\Rightarrow$ works, limiting the current is easy, but how to remain (or encode) forming ?

Limitations independent of implementation

(covered on the board)

- generic circuit with a current-saturated source



$$z \cdot i = v - v_g = \Delta v$$

Limitations independent of implementation

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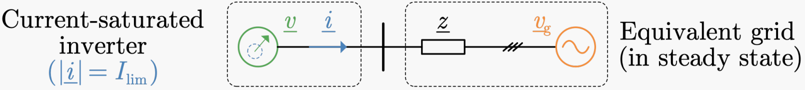
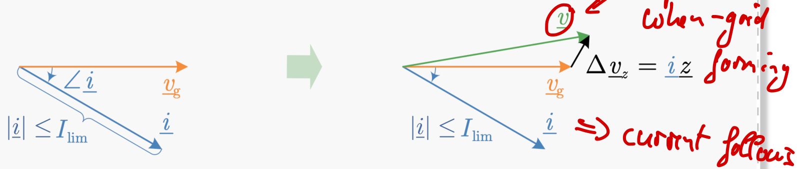
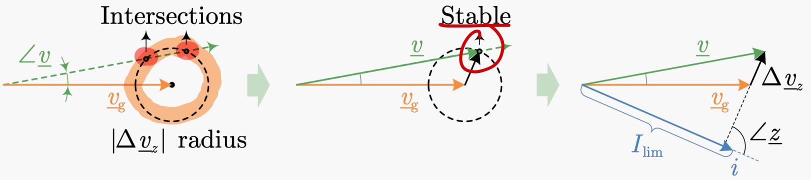


- circuit laws & vector diagram during normal operation $|\underline{i}| \leq I_{\text{lim}}$



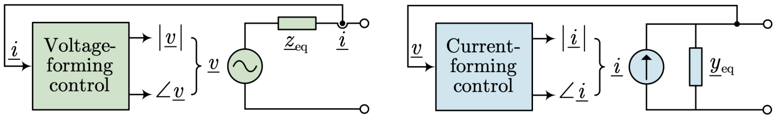
$z i = v - v_g = \Delta V$

- circuit laws & vector diagram during **current saturation** $|\underline{i}| = I_{\text{lim}}$



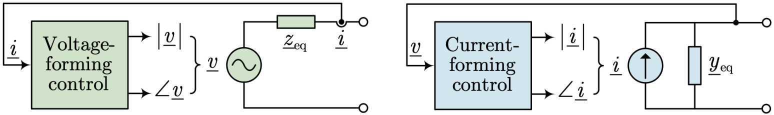
- during saturation: $|i| = I_{lim}$
- $\Rightarrow \|\Delta v\| = \|z \cdot i\| = \|z\| \cdot I_{lim}$ is fixed
- remaining free variables are $\angle v$ and $\angle i$
- any solution to $\angle v$ must intersect
- cross-forming: $|i| = I_{lim}$
  & control $\angle v$ (angle-forming)

Principled ways out of the dilemma



- **facts during current saturation** (independent of control architecture): (1) the current magnitude is imposed, (2) the voltage magnitude follows the circuit law ("voltage decline"), & (3) the voltage angle can still be imposed

Principled ways out of the dilemma



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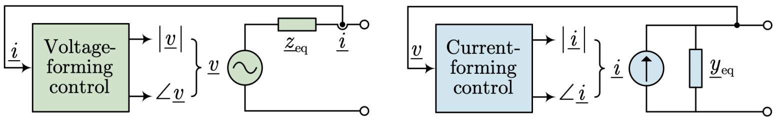

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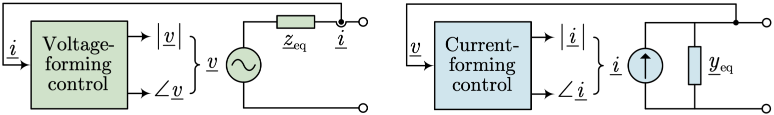
- **two principled remedies** during saturation

Principled ways out of the dilemma



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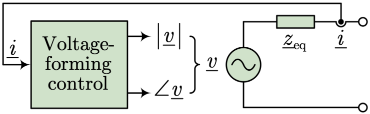
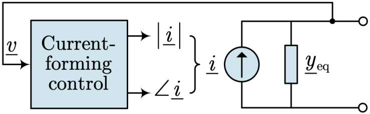
✗ form current angle $\angle\underline{i}$ $\sim$ **switch to grid-following** (issues listed before)

Principled ways out of the dilemma





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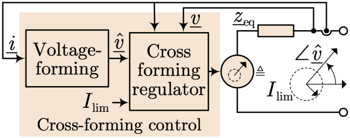
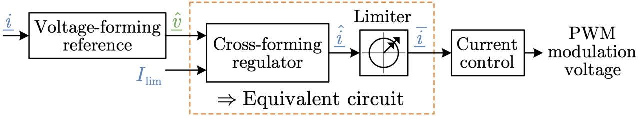
✗ form current angle $\angle \underline{i}$ $\sim$ **switch to grid-following** (issues listed before)

✓ **cross-forming control**: keep on forming voltage angle $\angle \underline{v}$ (= remain synchronizing) while current magnitude $|\underline{i}| = I_{\text{lim}}$ is imposed



Summary & cross-forming control specs

- generic cross-forming **control architecture**



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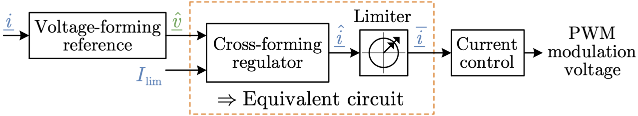

- **norminal equivalent circuit** presented to the grid: $\underline{z}_v \underline{i} = \hat{\underline{v}} - \underline{v}$

Summary & cross-forming control specs

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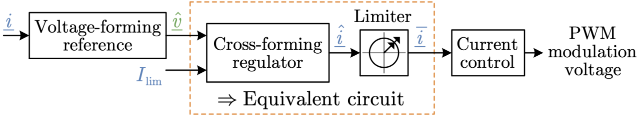
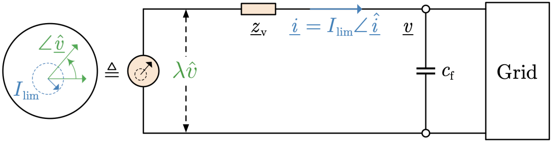


- **norminal equivalent circuit** presented to the grid: $\underline{z}_v \underline{i} = \underline{\hat{v}} - \underline{v}$

- **current-saturated equivalent circuit** presented to the grid: I_{lim} & $\angle \underline{\hat{v}}$ are imposed, reference voltage $\underline{\hat{v}}$ with unknown scaling λ & $\angle \underline{\hat{i}}$ follow circuit law



$$\underline{z}_v \underline{i} = \lambda \underline{\hat{v}} - \underline{v} \quad \& \quad |\underline{i}| = I_{\text{lim}}$$

Possible cross-forming implementation

- **equivalent circuit** during nominal operation: $\underline{z}_v \underline{i} = \underline{\hat{v}} - \underline{v}$

- **equivalent circuit** during saturation $|\underline{i}| = I_{\text{lim}}$: $\underline{z}_v \underline{i} = \lambda \underline{\hat{v}} - \underline{v}$ with scaling λ

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$\Leftrightarrow \mu \underline{z}_v \underline{\hat{i}} = \lambda \underline{\hat{v}} - \underline{v}$ with **degree of saturation** $\mu = \dfrac{\text{commanded current}}{\text{limited current}} = \dfrac{\underline{i}}{\underline{\hat{i}}} \in [0, 1]$

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$\longrightarrow$ **circuit characteristics preserved** if both current $\underline{i}$ & voltage $\underline{v}$ are scaled by μ: the former due to saturation & the latter through feedback of $\underline{v}/\mu$

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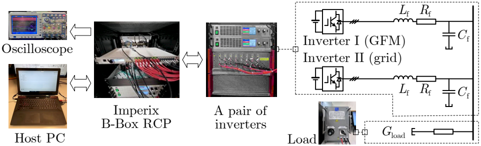
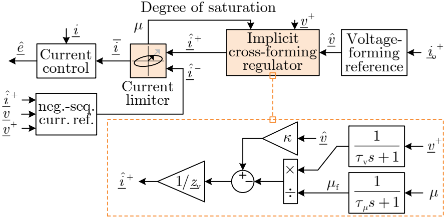
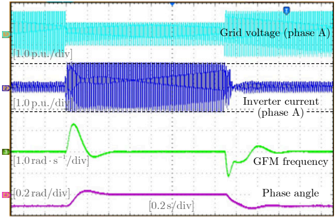
$\longrightarrow$ ...more to be said but requires a separate course ...

Experimental validations

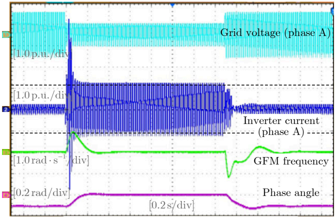




with cross-forming



without

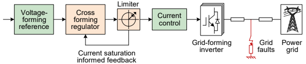


Details for further reading . . . & licensing ☺

ETH zürich

Licensing Opportunity

Fault ride-through and current limiting control of grid-forming inverters under grid faults



The controller comprises four modules, where the cross-forming regulator along with the current limiter preserves the voltage angle forming behavior and enforces the current magnitude forming behavior.

Application

This invention enables power inverters to control their *current magnitude* and *voltage angle* (i.e., "cross-forming"). With this, grid-forming inverters can quickly limit fault currents at a prescribed level and preserve voltage angle forming for grid synchronization and dynamic ancillary services provision (e.g., fault reactive current injection), during symmetrical or asymmetrical fault ride-through.

Features & Benefits

- Current magnitude forming and voltage angle forming
- Fast, able to fully utilize the overcurrent capability, adaptable to various disturbances, simple to implement, easy to tune, and robust in stability performance
- Constant virtual impedance facilitates stability analysis

Publications

- "Saturation-informed current-limiting control for grid-forming converters," *Electr. Power Syst. Res.*, 2024, 10.1016/j.epsr.2024.110746
- "Cross-forming control and fault current limiting for grid-forming inverters," submitted, 2024, arXiv.2404.13376
- Patent pending

ETH transfer
transfer@sl.ethz.ch
www.ethz.ch/transfer
Reference 2023-154

Invented by D-ITET: X. He, M.A. Desai, L. Huang, F. Dörfler

Technology Readiness Level

1 2 3 4 5 6 7 8 9

Background

Limiting the current of grid-forming inverters during grid disturbances is vital to prevent potential overcurrent damage. Moreover, grid-forming inverters should maintain grid-forming synchronization and supply ancillary services during fault ride-through as continuously as possible to satisfy the requirements of grid codes, even when the current reaches the limit. The technical challenge widely acknowledged in this regard involves limiting fault current, maintaining transient stability, and providing ancillary services simultaneously. Since grid-forming inverters play a crucial role in future grids and will be widely deployed in generation, transmission, distribution, and energy storage systems, there is a huge market need for high-performance grid-forming inverter products.

Invention

The controller comprises four modules (see the figure). The voltage-forming reference module aims to provide a voltage-forming reference. The cross-forming regulator module takes the voltage-forming reference, the voltage measurement, and the current saturation-informed feedback to generate a current reference based on a virtual admittance relationship. Thus, it ensures that the voltage angle forming behavior behind the virtual impedance is preserved, and meanwhile, the voltage magnitude is adaptively changed depending on overcurrent conditions. Furthermore, the current limiter enforces fast current magnitude limiting, and the inner current controller achieves fast current tracking. In this way, the controller enables grid-forming inverters to safely and stably ride through grid faults and quickly provide ancillary services such as fault currents. Moreover, the resulting virtual impedance is constant, allowing users to directly apply existing methods for transient stability analysis. The control code of this invention has been tested and validated in a prototype converter laboratory platform.

Cross-Forming Control and Fault Current Limiting for Grid-Forming Inverters

Xiuqiang He, *Member, IEEE,* Maitraya Avadhut Desai, *Graduate Student Member, IEEE,* Linbin Huang, *Member, IEEE,* and Florian Dörfler, *Senior Member, IEEE*

***Abstract*—This article proposes a "cross-forming" control concept for grid-forming inverters operating against grid faults. Cross-forming refers to *voltage angle forming* and *current magnitude forming*. It differs from classical grid-forming and grid-following paradigms that feature voltage magnitude-and-angle forming and voltage magnitude-and-angle following (or current magnitude-and-angle forming), respectively. The cross-forming concept addresses the need for inverters to remain grid-forming (particularly *voltage angle forming*, as required by grid codes) while managing *fault current limitation*. Simple and feasible cross-forming control implementations are proposed, enabling inverters to quickly limit fault currents to a prescribed level while preserving voltage angle forming for grid-forming synchronization and providing dynamic ancillary services, during symmetrical or asymmetrical fault ride-through. Moreover, the cross-forming control yields an equivalent system featuring a constant virtual impedance and a "normal form" representation, allowing for the extension of previously established transient stability results to include scenarios involving current saturation. Simulations and experiments validate the efficacy of the proposed cross-forming control implementations.**

A. Related Work

When grid-forming inverters are operated under normal grid conditions (i.e., the current is not saturated), managing grid-forming synchronization and providing grid-forming ancillary services is by now well understood. In respect thereof, the transient stability of grid-forming inverters has been widely investigated in the literature; see [5] for a comparative study and [6], [7] for a review. In parallel, the provision of dynamic ancillary services for grid-forming inverters under normal operating conditions has also been extensively explored in the literature; see [8] for a survey. In contrast to normal operating conditions, the critical challenge under grid fault conditions arises from current limiting. In the literature, the current limiting of grid-forming inverters is addressed with three typical strategies: 1) adaptive/threshold virtual impedance [9], [10]; 2) current limiter cascaded with virtual admittance [11]–[15]; and 3) current-forming voltage-following control [16]–[22]. Their different merits and shortcoming are described below.

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Saturation-informed current-limiting control for grid-forming converters

Maitraya Avadhut Desai, Xiuqiang He *, Linbin Huang, Florian Dörfler

Automatic Control Laboratory, ETH Zurich, 8092 Zurich, Switzerland

ARTICLE INFO

Keywords:
Complex-droop control
Current limiting
dVOC
Grid-forming converter
Transient stability

ABSTRACT

In this paper, we investigate the transient stability of a state-of-the-art grid-forming complex-droop control (i.e., dispatchable virtual oscillator control, dVOC) under current saturation. We quantify the saturation level of a converter by introducing the concept of degree of saturation (DoS), and we propose a provably stable current-limiting control with saturation-informed feedback, which feeds the degree of saturation back to the inner voltage-control loop and the outer grid-forming loop. As a result, although the output current is saturated, the voltage phase angle can still be generated from an internal virtual voltage-source node that is governed by an equivalent complex-droop control. We prove that the proposed control achieves transient stability during current saturation under grid faults. We also provide parametric stability conditions for multi-converter systems under grid-connected and islanded scenarios. The stability performance of the current-limiting control is validated with various case studies.

Synopsis & lessons learnt on device level

① **converter** $\neq$ **flywheel**: very different actuation & energy storage

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② take **dc voltage into account**: robust imbalance signal akin to frequency

Synopsis & lessons learnt on device level

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2. take **dc voltage into account**: robust imbalance signal akin to frequency

3. **multivariable design** instead of decoupling: simple but results in huge gains
   $\rightarrow$ based on optimization & account for grid-forming / following specifications
   $\rightarrow$ motivates **architecture-free definitions** of grid connection requirements, grid codes, & ancillary service specifications (talk to Verena in the audience)

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④ hard problem: satisfy **current constraints** & remain grid-forming post-fault
$\rightarrow$ cross-forming control as a principled remedy

Synopsis & lessons learnt on device level

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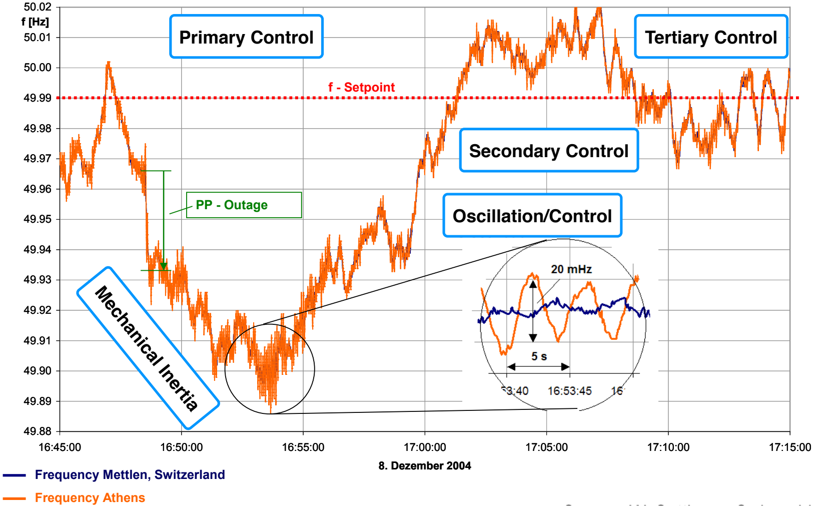
4. hard problem: satisfy **current constraints** & remain grid-forming post-fault
   $\rightarrow$ cross-forming control as a principled remedy
5. synchronization is only the beginning: what to do once sync'd ? **services !**

Outline

- Motivation: Challenges & Game Changers
- Power Converter Modeling & Control Specifications
- **Device-Level: Control of Converter-Interfaced Generation**
- System-Level: Ancillary Services in Low-Inertia Grids

Hook curve & services in conventional system

source: W. Sattinger, Swissgrid

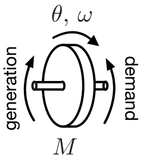


Naive insight: we are loosing inertia

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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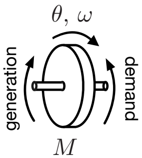
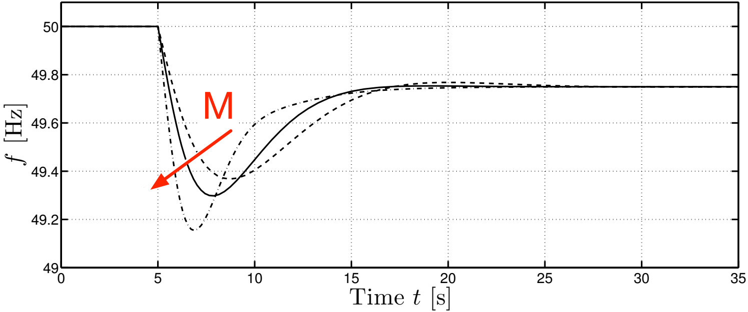
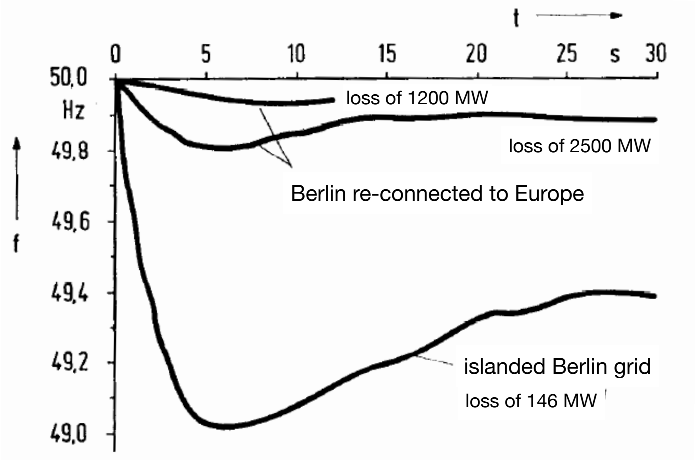


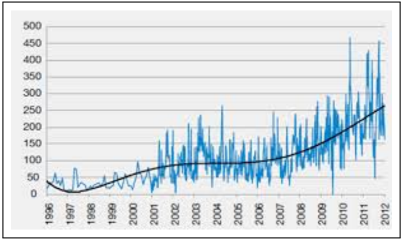


Berlin post-fault curves: before & after



Source: *Energie-Museum Berlin*

Low-inertia issues close to home



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

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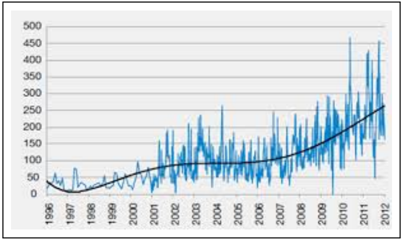

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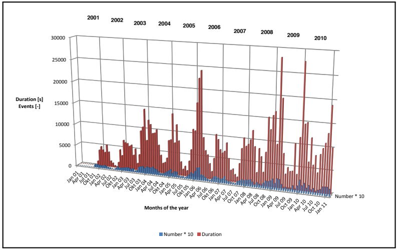

same in Switzerland (source: Swissgrid)

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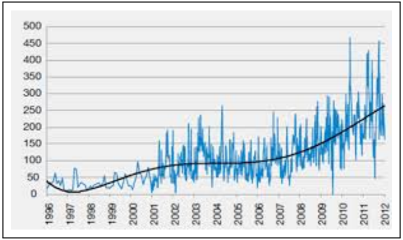

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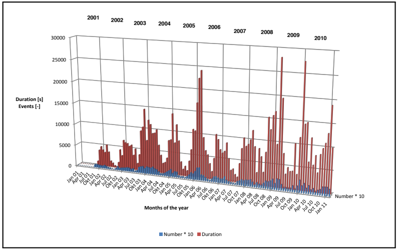

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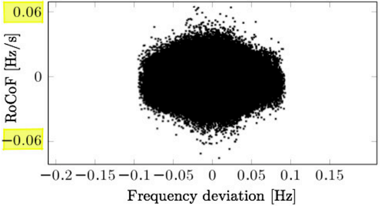
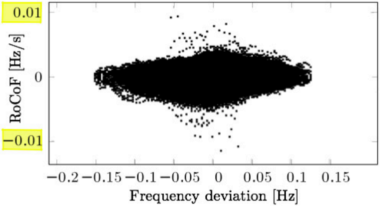


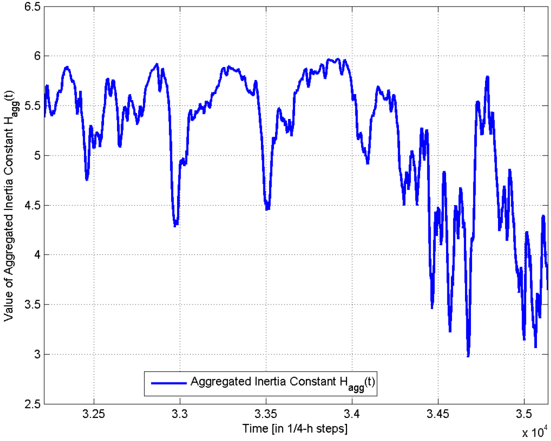
a day in Ireland (source: F. Emiliano)



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

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

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

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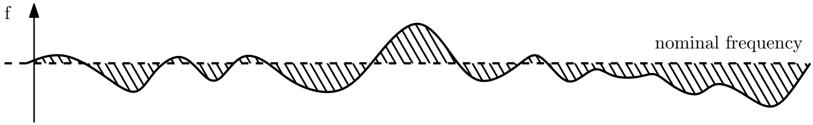

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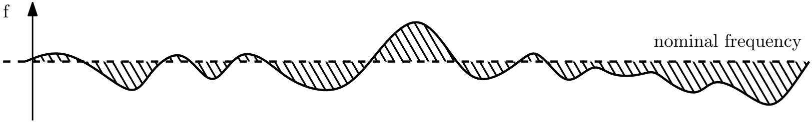
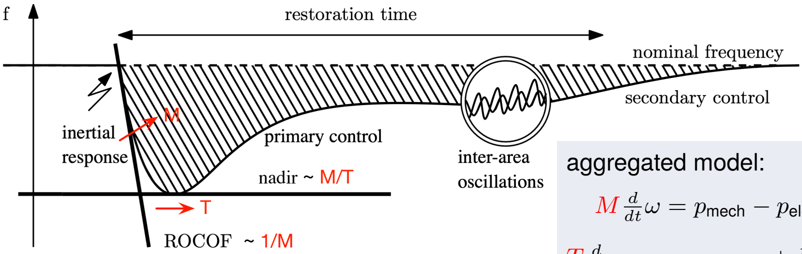
→ certainly more **brittle** behavior & for very low inertia levels **anything** may happen

→ on the positive side: **actuation is much faster** !



Second-order observations beyond naive insight



aggregated model:

$$M \frac{d}{dt}\omega = p_{\text{mech}} - p_{\text{elec}}$$

$$T \frac{d}{dt}p_{\text{mech}} = -p_{\text{mech}} + K\omega$$

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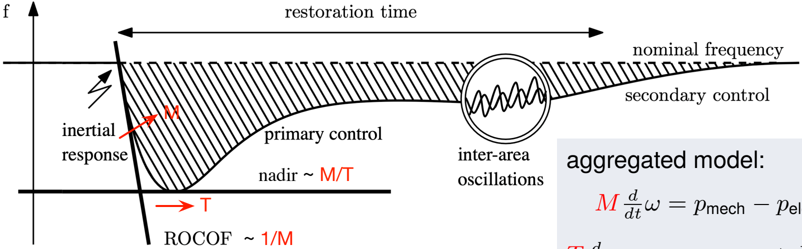

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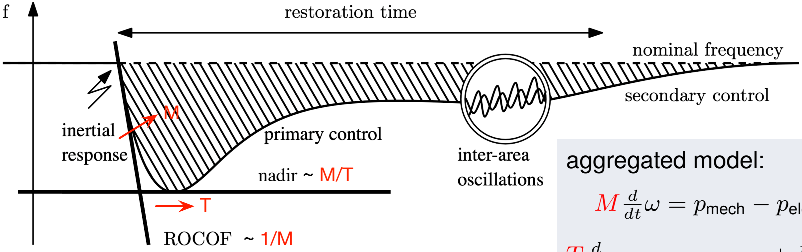

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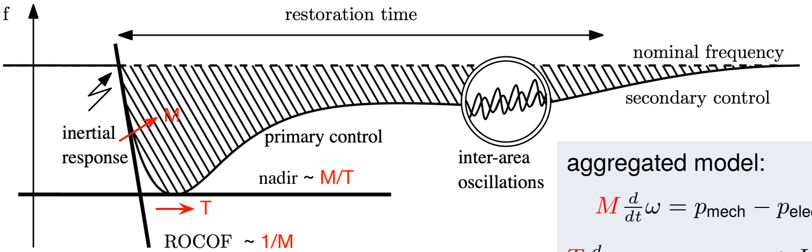

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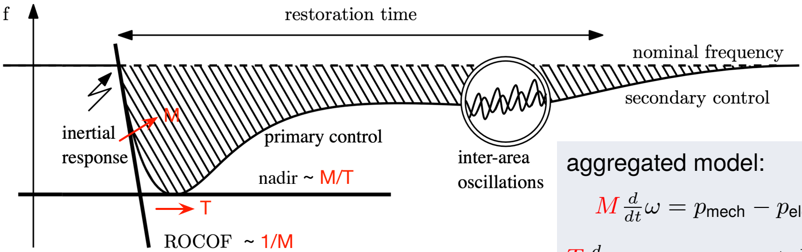

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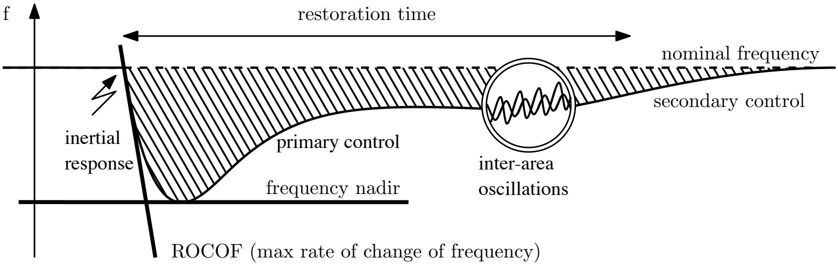
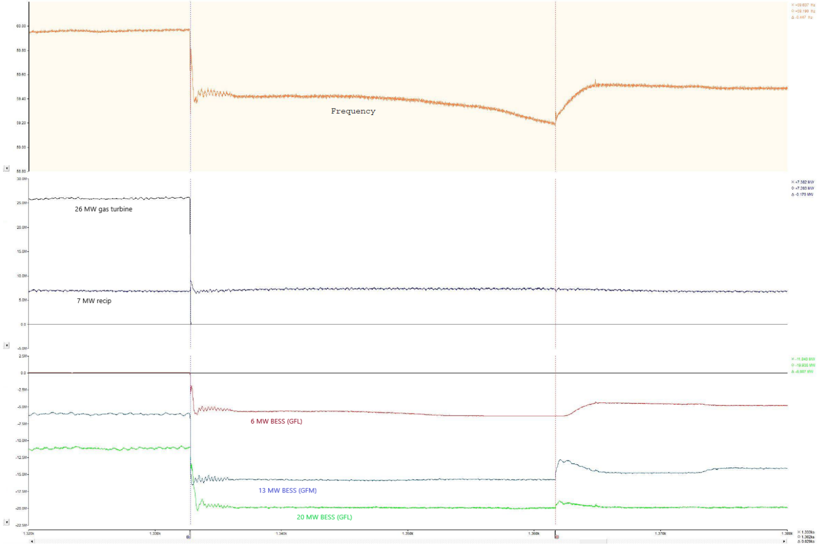
$\rightarrow$ new physical phenomena $\rightarrow$ **new metrics & new ancillary services** needed

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



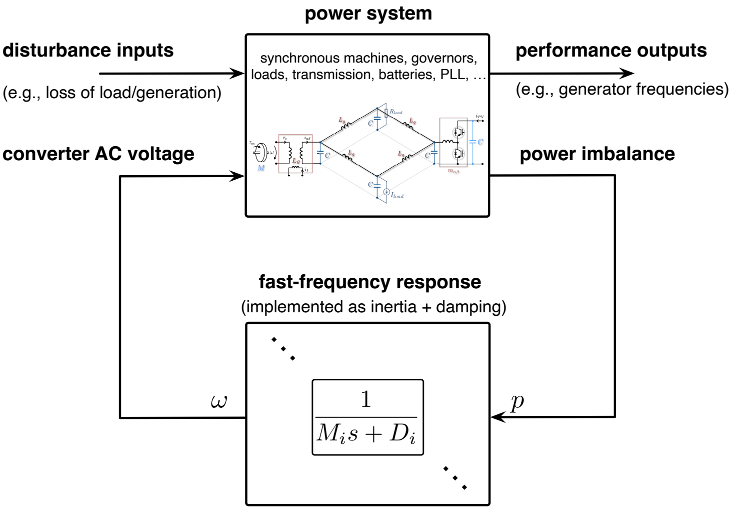
Fact: no more hook curves in low-inertia systems

source: confidential – but you can make your guesses



Fast frequency response provided by converters

can be implemented in either grid-forming or following paradigm



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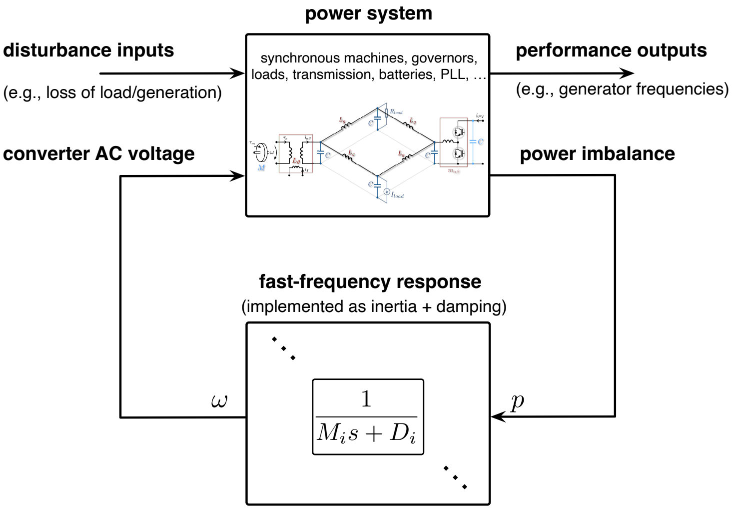
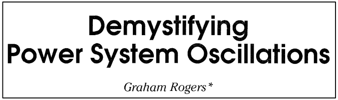


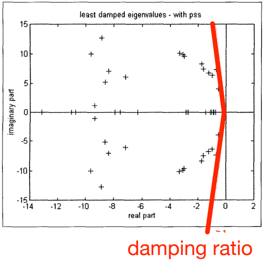
which metric(s) should we optimize when tuning controls ?

metrics

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


Demystifying Power System Oscillations

*Graham Rogers**



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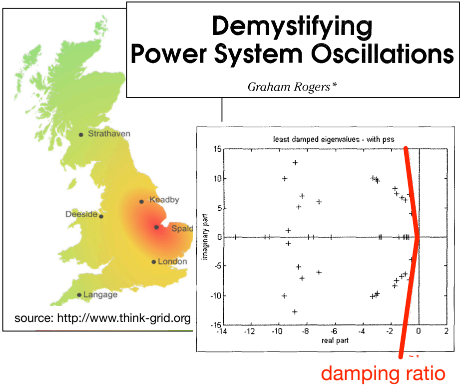

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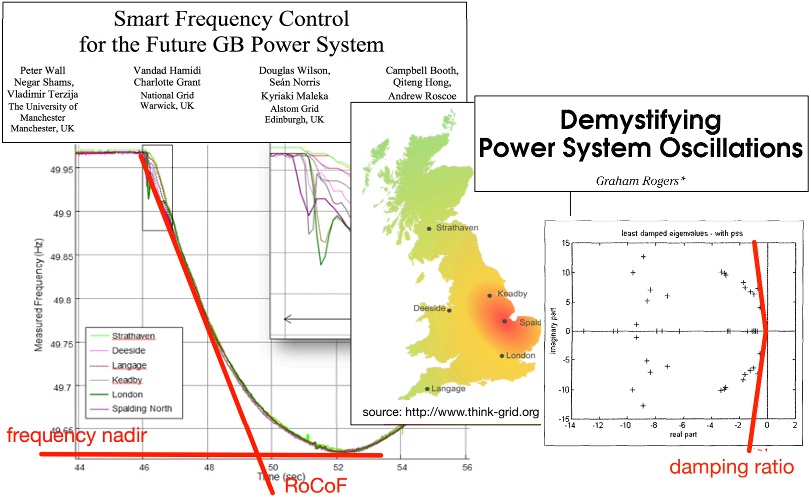

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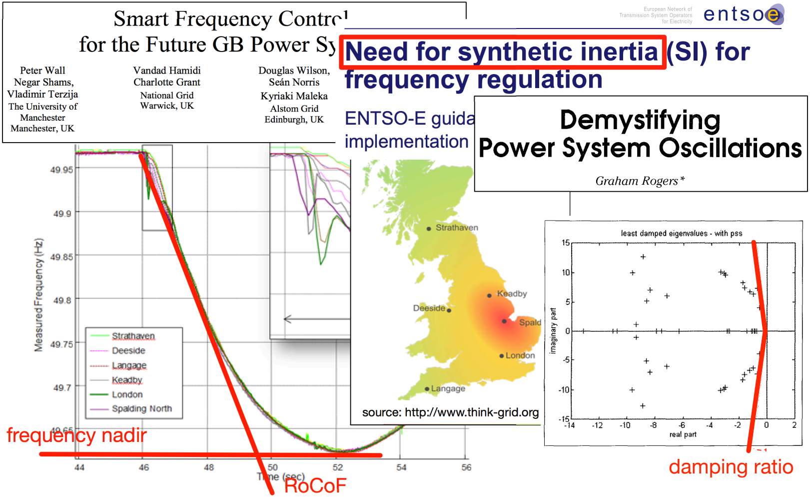
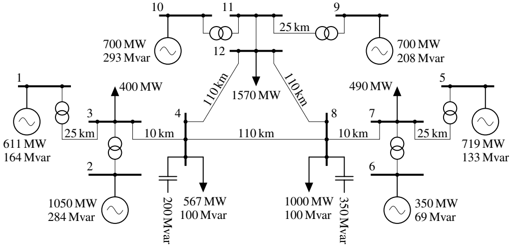


are these suitable metrics ?

let’s look at a case study

Futility of traditional metrics



- Kundur case study with 3rd area & $\sim$ 40s of rotational inertia
- removed 28s of inertia which can be re-allocated as virtual inertia
- study 2 virtual inertia allocations

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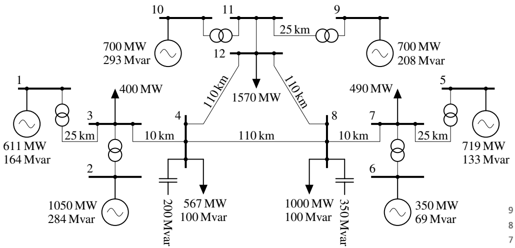

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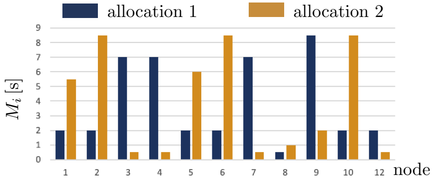

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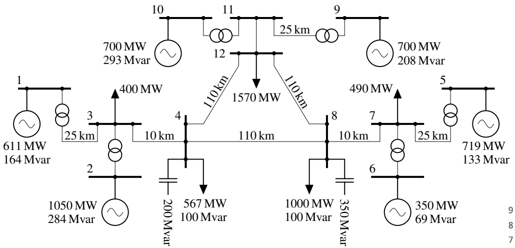

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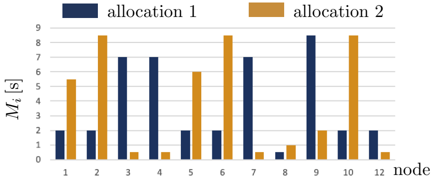
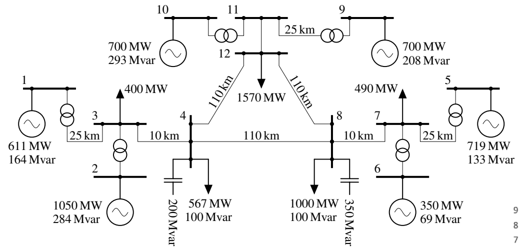


metrics	allocation 1	allocation 2
total inertia	40.85 s	40.85 s

Futility of traditional metrics



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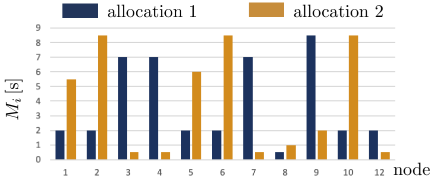

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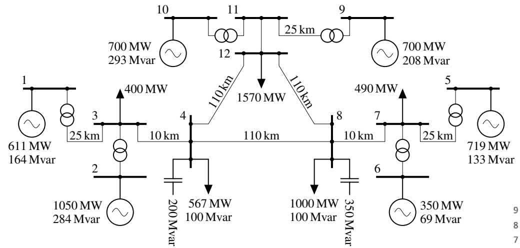
Futility of traditional metrics



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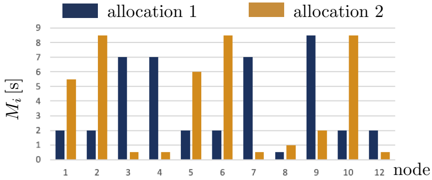

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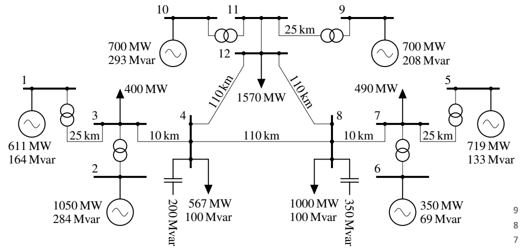

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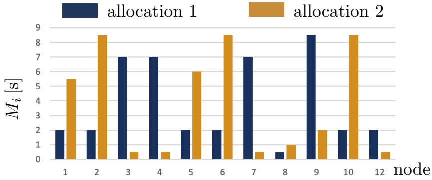

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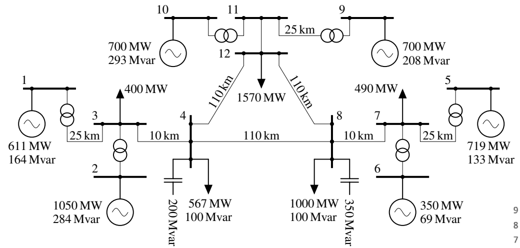

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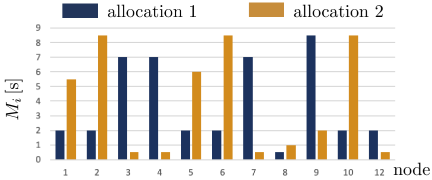

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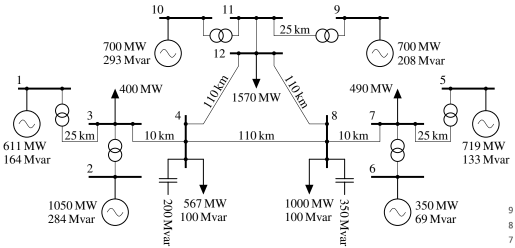

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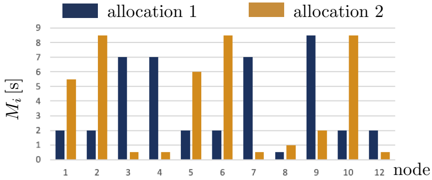

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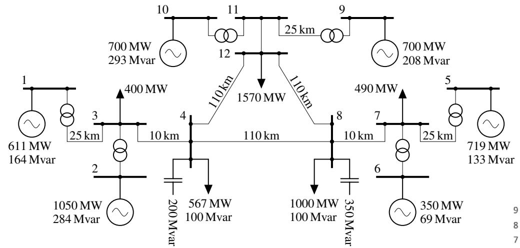

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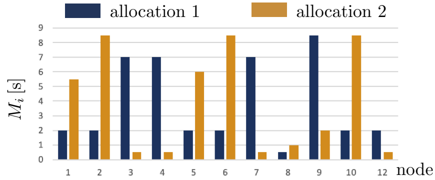

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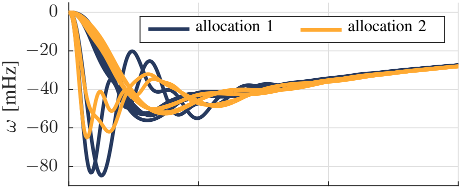

comparison for 100 MW load step at bus 7

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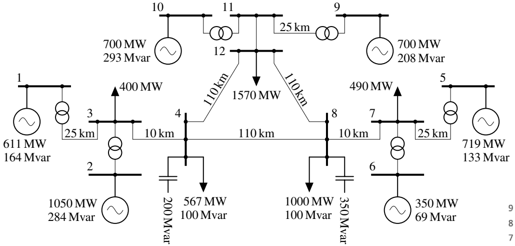

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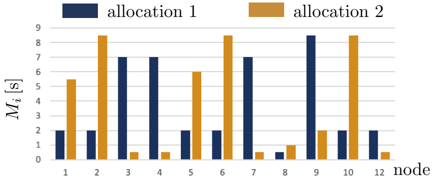

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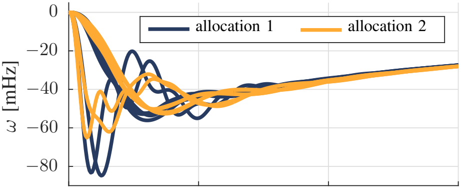
traditional metrics ambiguous → **discard**



comparison for 100 MW load step at bus 7

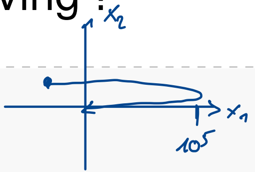
Why eigenvalues can be deceiving ?

(covered on the board)

Example:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} -100 & * \\ 0 & -10 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

($* = 10^5$)



Eigenvalues are $\{-100, -10\}$ for all choices of $*$

$$x_2(t) = e^{-10t} x_{20}$$

$$x_1(t) = e^{-100t} x_{10} + 10^5 \int_0^t e^{-(t-\tau)} x_2(\tau)\, d\tau$$

$\rightarrow$ eigenvalues do not say much about transient behavior

Example with disturbance:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} -100 & 10^5 \\ 0 & -10 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \eta \end{bmatrix}$$

(η: disturbance)

$\rightarrow$ disturbance gets multiplied by 10^5 before hitting x_1

More useful metrics: system norms

- from step responses in a conventional power system to more modern (1980) **system norms** quantifying the effect of shocks on variables of interest

disturbances: impulse (fault), step (loss of generation), stochastic signal (renewables)

performance outputs: signal energy or peak in time / frequency domain of output

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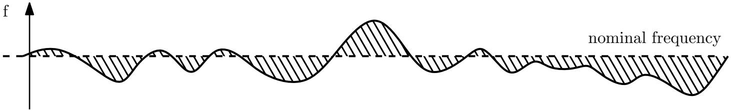
- **example:** as a result of fault choose best fast frequency response to minimize

$$\int_0^\infty \{\text{frequency deviation}\}^2 + \{\text{coherency: deviation from COI}\}^2 + \{\text{control effort}\}^2 \, dt$$



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- **practical**: efficiently computable, analysis & design, & captures relevant shocks

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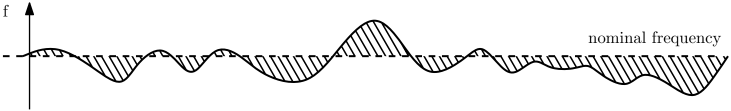
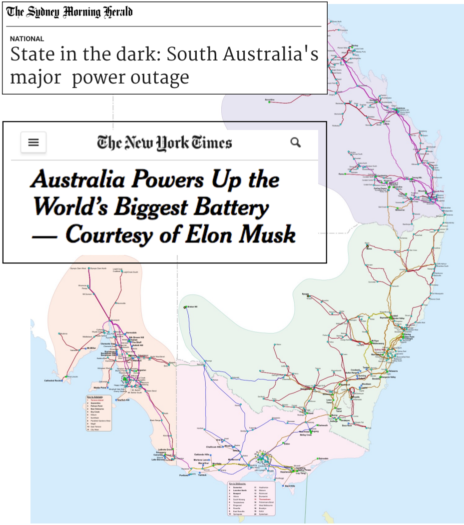
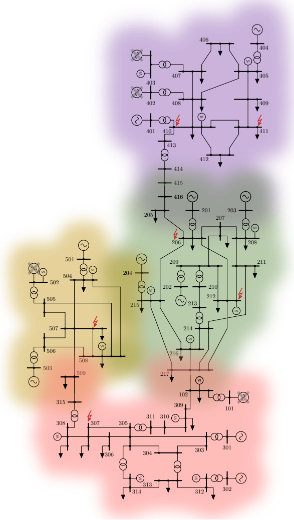


fast frequency response
based on system norms

Case-study: South-East Australian Grid



grid topology



simulation model

Closed-loop with optimal fast frequency response

model & fast frequency response

- **replaced** some machines with **converters** & (forming or following) fast frequency response: **virtual inertia + damping**

$$\text{frequency} = \frac{1}{M\,s + D}\ \text{power}$$

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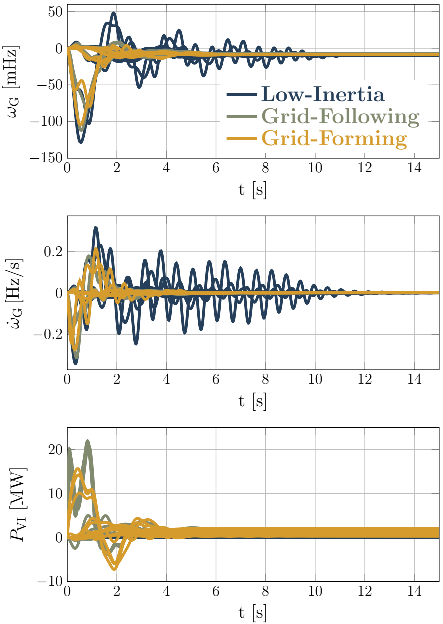

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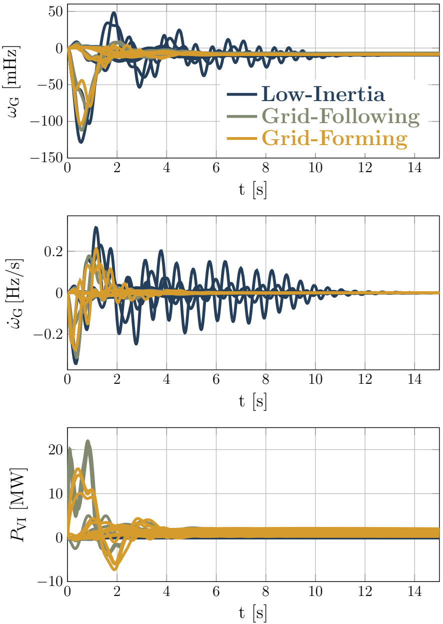

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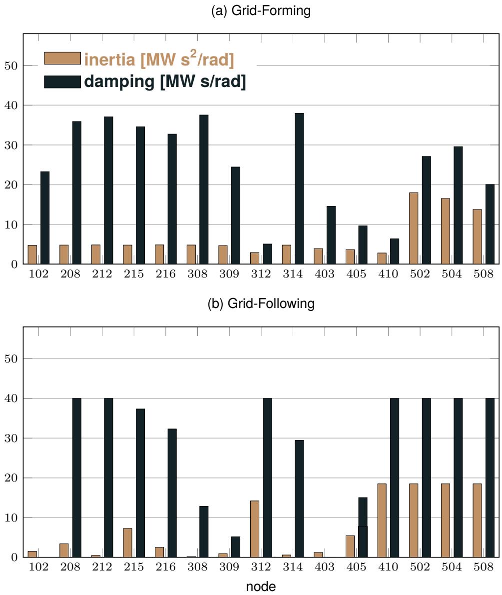
observations

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

→ **forming beats following** in nadir, RoCoF, & peak power

Optimal allocation of virtual inertia + damping



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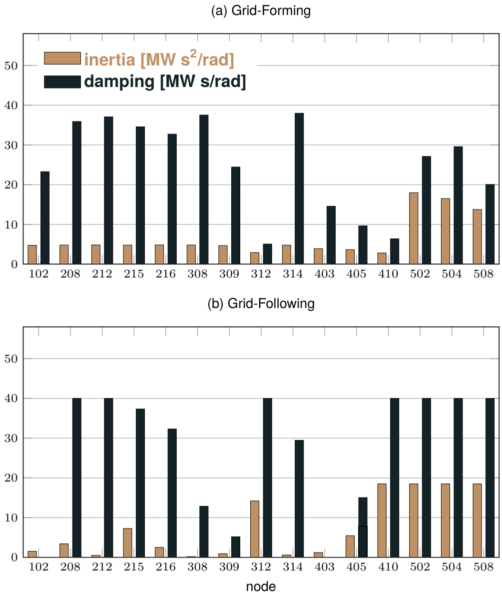
- both control modes allocate virtual inertia in (blackout & battery) **area 5**

Optimal allocation of virtual inertia + damping



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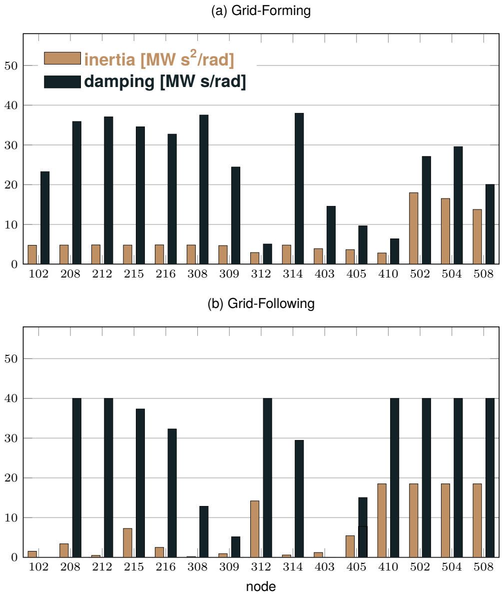

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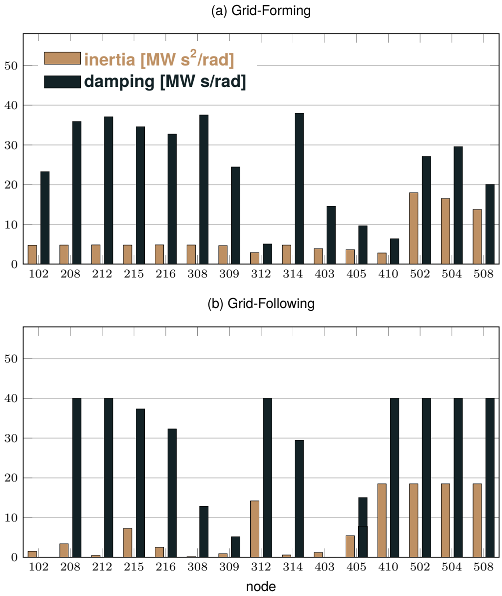

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→ implications for pricing & markets

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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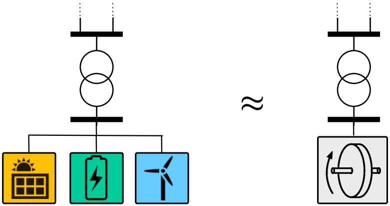
some of basic questions settled → lots of **emergent literature** on

- 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

who should provide these services ?

Services from Dynamic Virtual Power Plant (DVPP)



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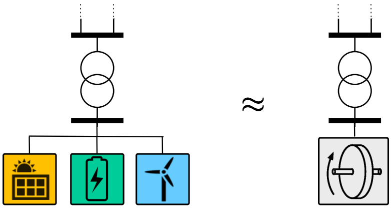
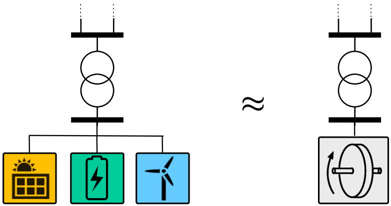


examples

- frequency containment with non-minimum phase hydro & batteries (for fast response)
- wind providing fast frequency response & voltage support augmented with storage
- hybrid power plants, e.g., PV + battery + supercap

Services from Dynamic Virtual Power Plant (DVPP)

DVPP: coordinate heterogeneous set of DERs to collectively provide dynamic ancillary services



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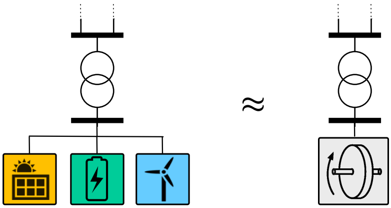

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  - reliable provide services consistently across all power & energy levels and all time scales
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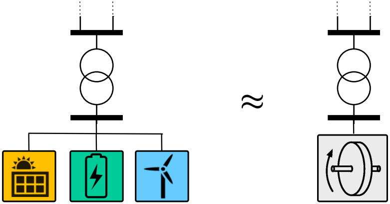

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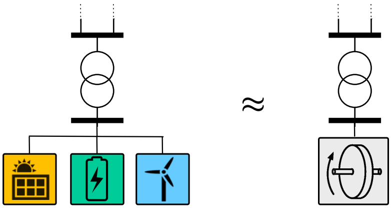

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- **coordination** aspect
  - decentralized control implementation
  - real-time adaptation to variable DVPP generation & ambient grid conditions

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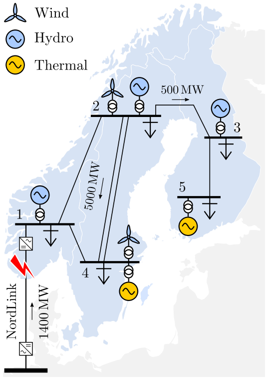
Nordic case study



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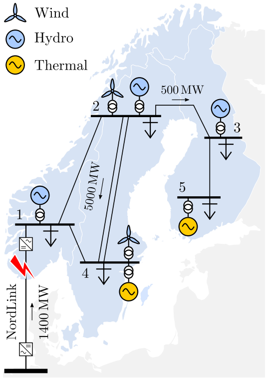
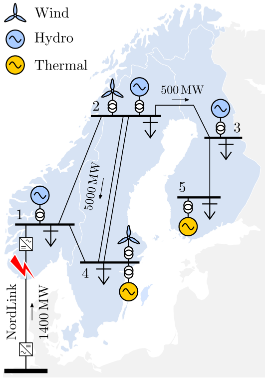


- **FCR-D service**

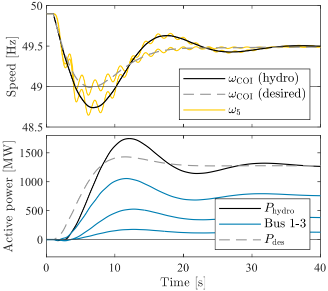
  → desired behavior

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

Nordic case study



- well-known **issue:** actuation of hydro is non-minimum phase
  $\rightarrow$ initial power surge opposes control
  $\rightarrow$ unsatisfactory response



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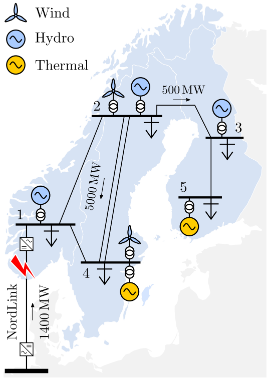

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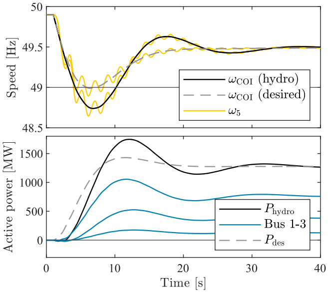

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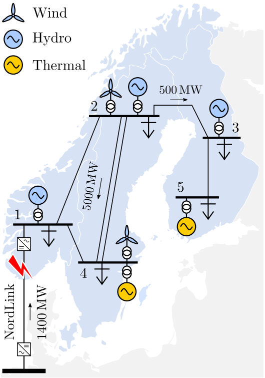

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- better **DVPP solution**: coordinate hydro & wind to cover all time scales

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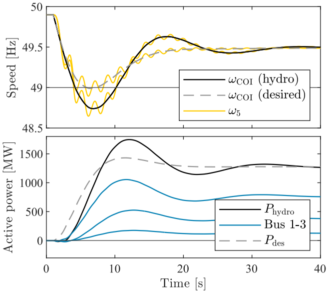
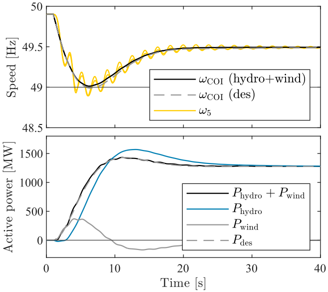
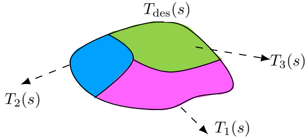




Enabler: dynamic & adaptive participation factors

- specify desired **aggregate DVPP behavior** $T_{\text{des}}(s)$, e.g., a desired fast frequency response $p \mapsto f$



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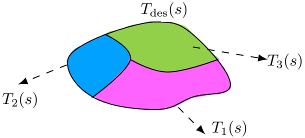

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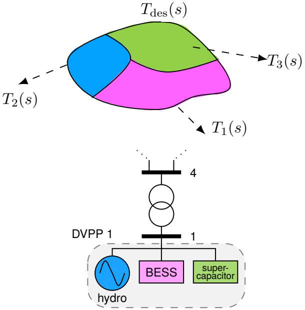

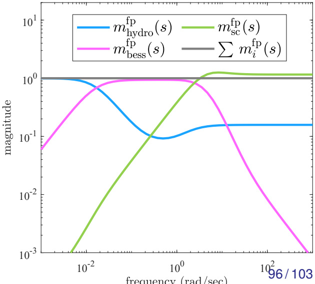

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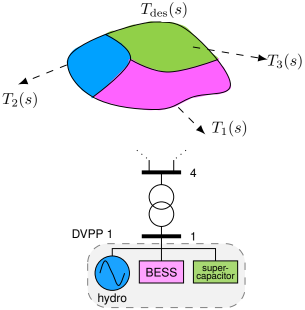

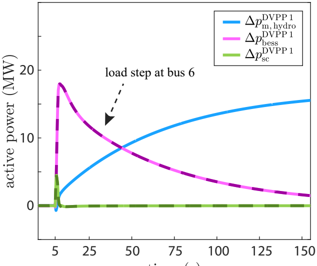

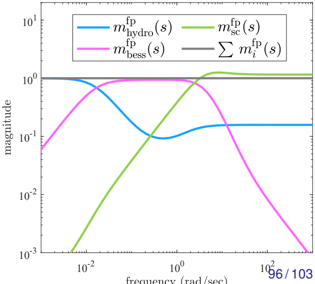

DVPP Control Design

(covered on the board)

... out of time today...

Starting points 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

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

B. Marinescu*
Ecole Centrale Nantes-LS2N, Fra

H. Schu
HTW-Berlin, G

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

Weilin Zhong [1], Junru Chen [2], Muyang Liu [2], Mohammed Ahsan Adib Murad [3] and Federico Milano [1,*]

[1] Room 157, School of Electrical and Electronic Engineering, University College Dublin, Belfield, D04 V1W8 Dublin, Ireland; weilin.zhong@ucdconnect.ie
[2] School of Electrical Engineering, Xinjiang University, Ürümchi 830046, China; junru.chen@xju.edu.cn (J.C.); muyang.liu@xju.edu.cn (M.L.)
[3] DIgSILENT GmbH, 72810 Gomaringen, Germany; mohammed.murad@ucdconnect.ie

quency control strategy for Virtual Power Plants
Resources (DERs), e.g., Solar Photo-Voltaic Gen-
Energy Storage System (ESS). The objective is
the overall power system. The robustness of the
arlo analysis and a detailed modeling of stochastic
diance. The impact of communication delays of a
different bandwidths is also discussed and evalu-
of the WSCC 9-bus test system with inclusion of
with inclusion of a variety of DERs.

Grid forming capability of power park modules

Final version | 3 May 2024

entsoe

3. The active power change at the terminals of the PPM may be provided by all or a limited number of DUT, as long as the performance criteria at the terminals of the PPM are met.
4. If the concept of a distributed virtual power plant (DVPP[23]) is accepted by a TSO, in coordination with the relevant system operator, the location of the provision of the inertia contribution may differ from the location of the PPM terminals.

Synopsis & lessons learnt on system level

1. initial literature was all about inertia ...but we **should not extrapolate from the old system**: total inertia & conventional metrics might be misleading

2. **system norms** are more useful, practical, & sharper metrics for both system analysis & optimal design of fast frequency response

3. **spatial allocation & tuning** of fast frequency response & **forming vs. following** behavior matters more than total amount of inertia & damping

4. **dynamic virtual power plants** to distribute ancillary services across heterogeneous DERs collectively covering all power levels & time scales

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5. wide open: **specification of future ancillary services**, e.g., desired input / output responses + **share & location of grid-forming** sources

Preliminary ideas on future ancillary service specs

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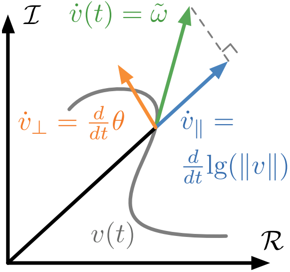

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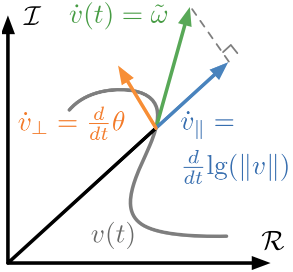

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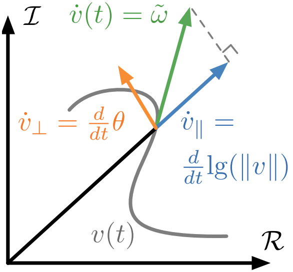

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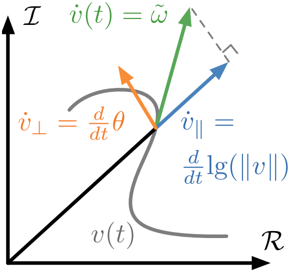

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$\rightarrow$ ideally seek **architecture-free & computationally tractable** definitions, e.g.,

minimize $\textit{cost}(\tilde{\omega}, \tilde{s})$ *subject to device & operational constraints*

Conclusions

- **do not think only of "inertia"** when designing converter controls, analyzing power systems, or specifying ancillary services
- rather: **adopt more system-theoretic & computational mind-set**: specify desired responses & use optimization + multivariable control
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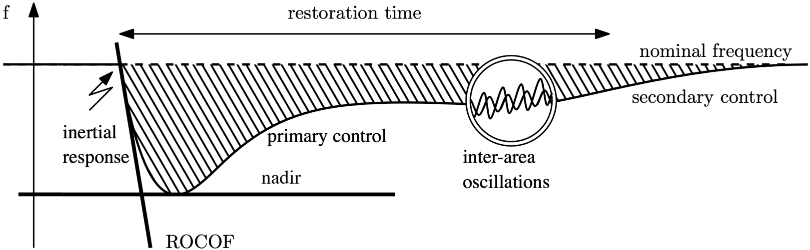
- last: **free yourself from textbook plots** – tomorrow's system will be different



finally . . . recall


POWER IS NOTHING WITHOUT CONTROL