

Low-Inertia Power Systems

Florian Dörfler, ETH Zurich

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

Outline

- Motivation: Challenges & Game Changers
- Power Converter Modeling & Control Specifications
- Elements of Power Electronics Control

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- Power Converter Modeling & Control Specifications
- Elements of Power Electronics Control

Replacing the system foundation

fuel

− **not sustainable**

renewables

+ **sustainable**

Replacing the system foundation

fuel

− **not sustainable**

\+ **central & dispatchable** generation

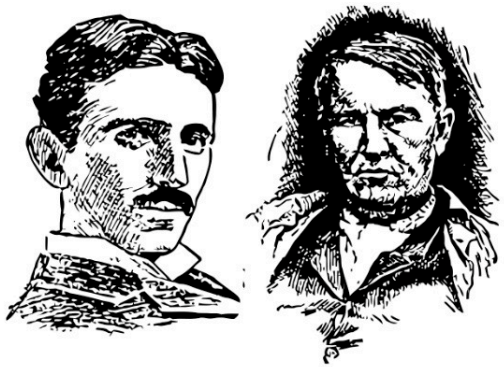
renewables

\+ **sustainable**

− **distributed & variable** generation

Replacing the system foundation







fuel & synchronous machines

− **not sustainable**

\+ **central & dispatchable** generation

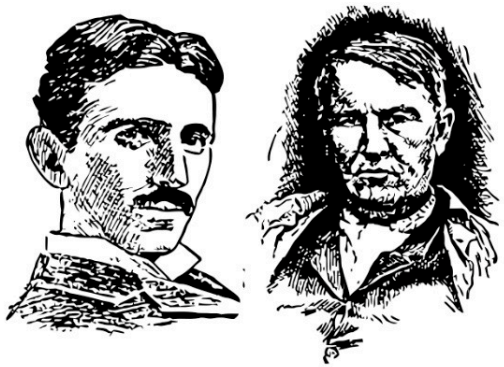
renewables & power electronics

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Replacing the system foundation







fuel & synchronous machines

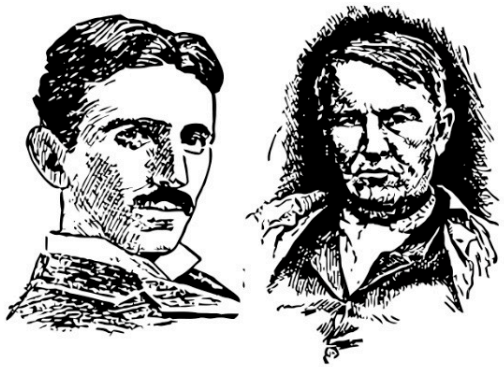
- − **not sustainable**
- \+ **central & dispatchable** generation
- \+ **large** rotational **inertia** as buffer

renewables & power electronics

- \+ **sustainable**
- − **distributed & variable** generation
- − almost **no energy storage**

Replacing the system foundation







fuel & synchronous machines

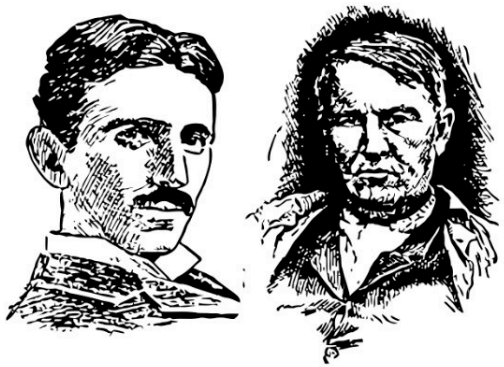
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- \+ **self-synchronize** through the **grid**

renewables & power electronics

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

Replacing the system foundation







fuel & synchronous machines

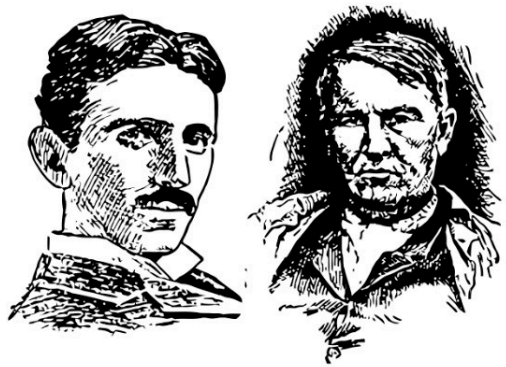
- − **not sustainable**
- \+ **central & dispatchable** generation
- \+ **large** rotational **inertia** as buffer
- \+ **self-synchronize** through the **grid**
- \+ **resilient** voltage / frequency **control**

renewables & power electronics

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

Replacing the system foundation







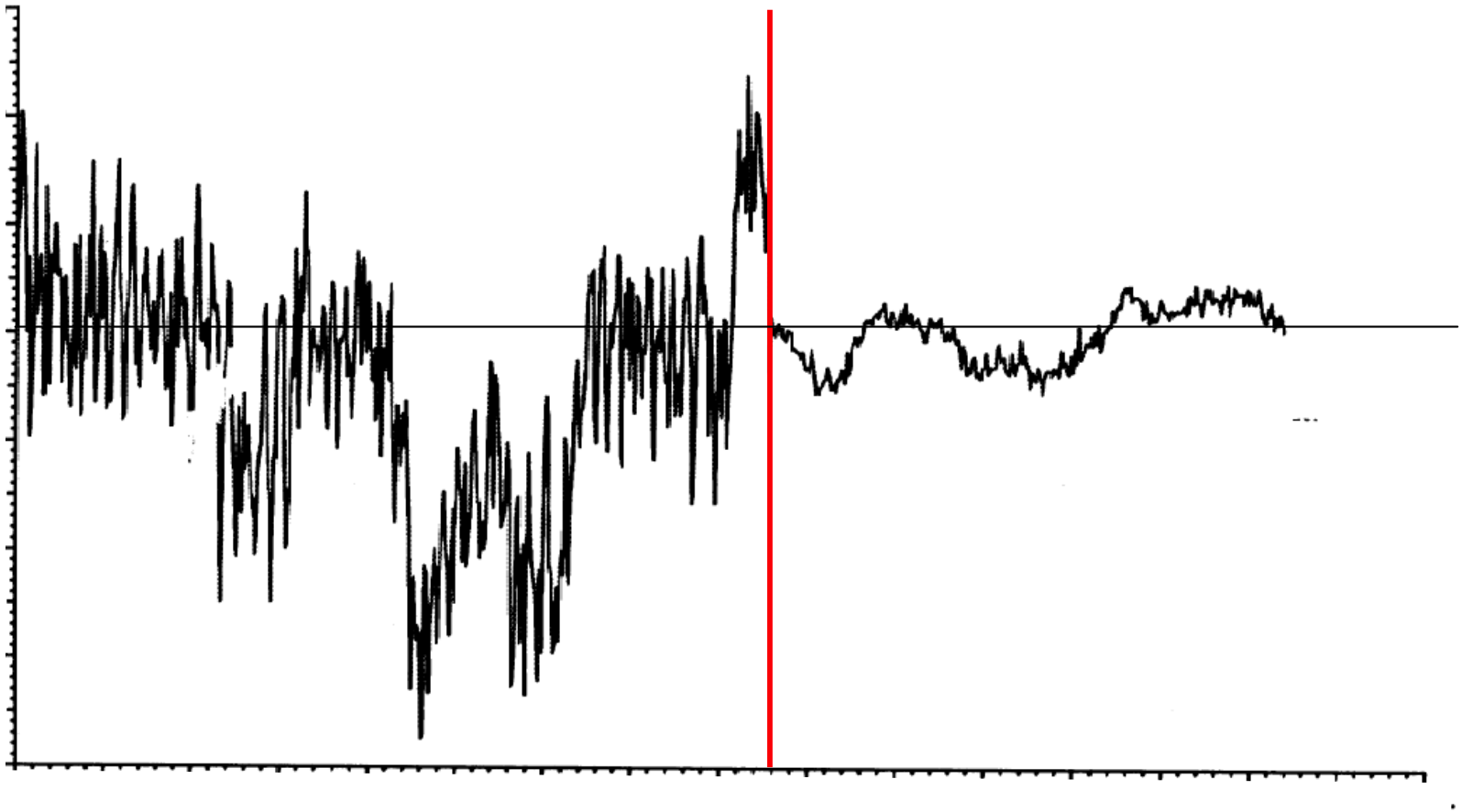
fuel & synchronous machines

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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

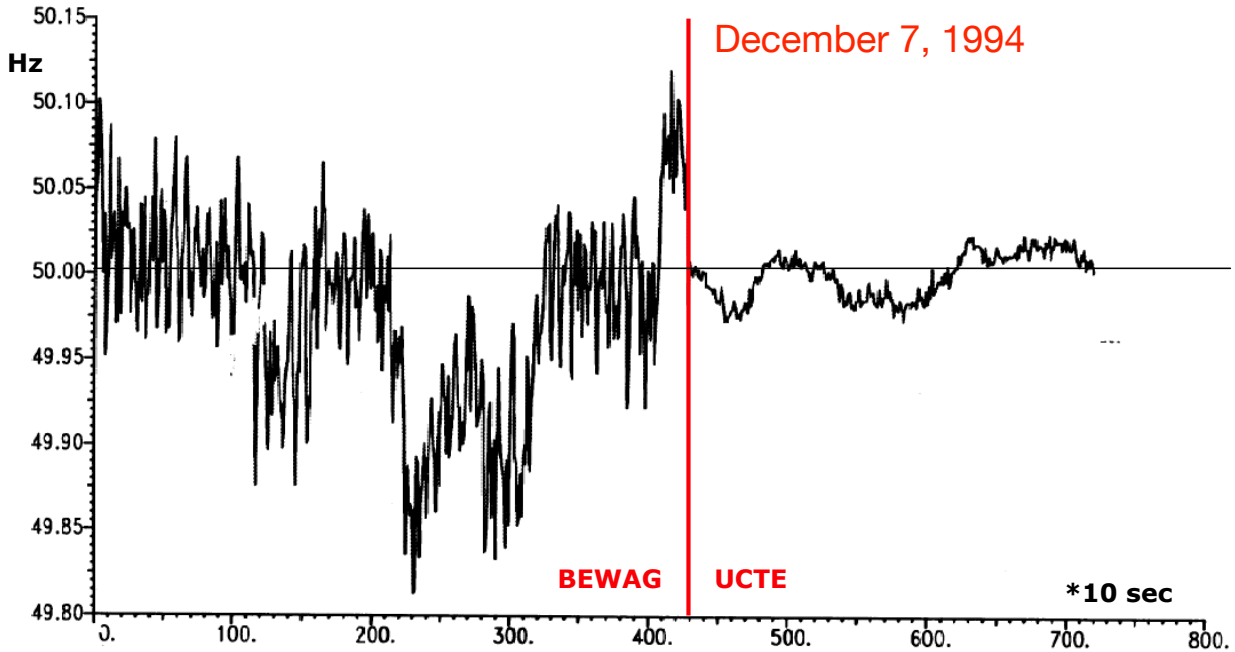
- \+ **sustainable**
- − **distributed & variable** generation
- − almost **no energy storage**
- − **no** inherent **self-synchronization**
- − **fragile** voltage / frequency **control**
- \+ **fast / flexible / modular control**

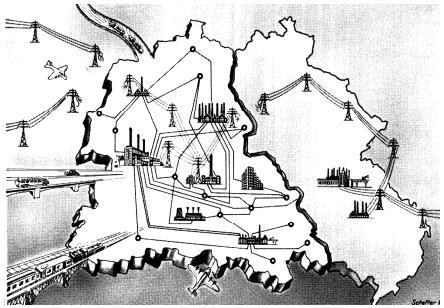
What do we see here ?



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**

The concerns are not hypothetical


theguardian

South Australia

South Australia blackout: entire state left without power after storms

key events

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

The concerns are not hypothetical

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

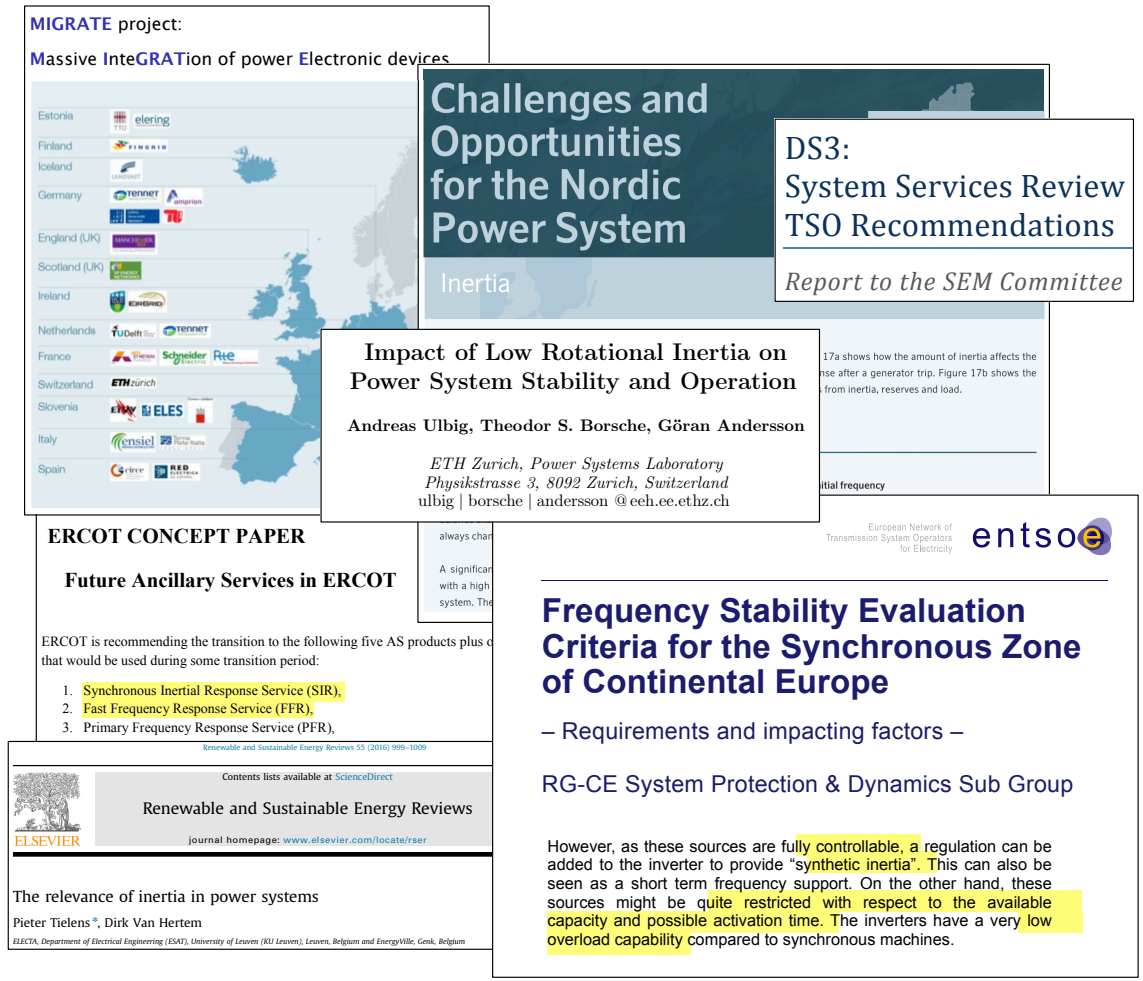
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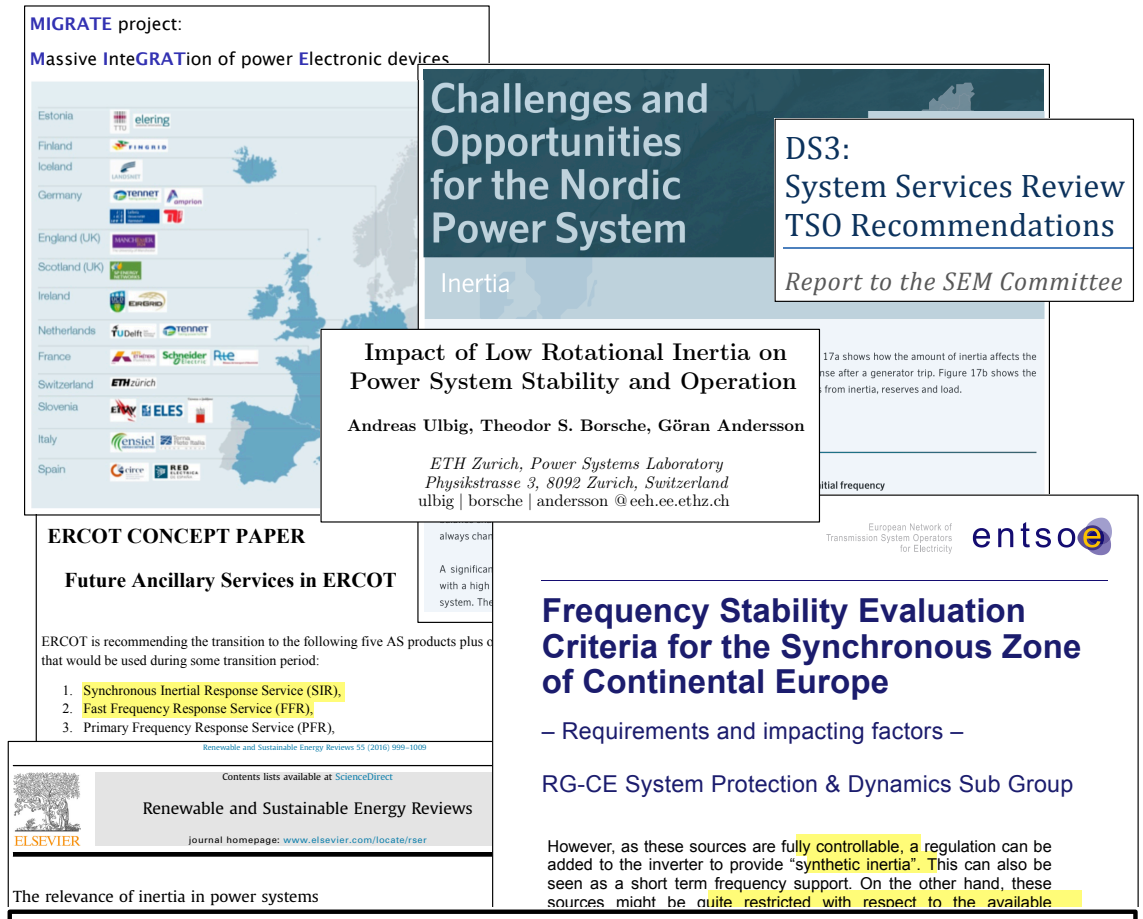
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Biblis A generator stabilizes the grid as a synchronous condenser

amprion SIEMENS

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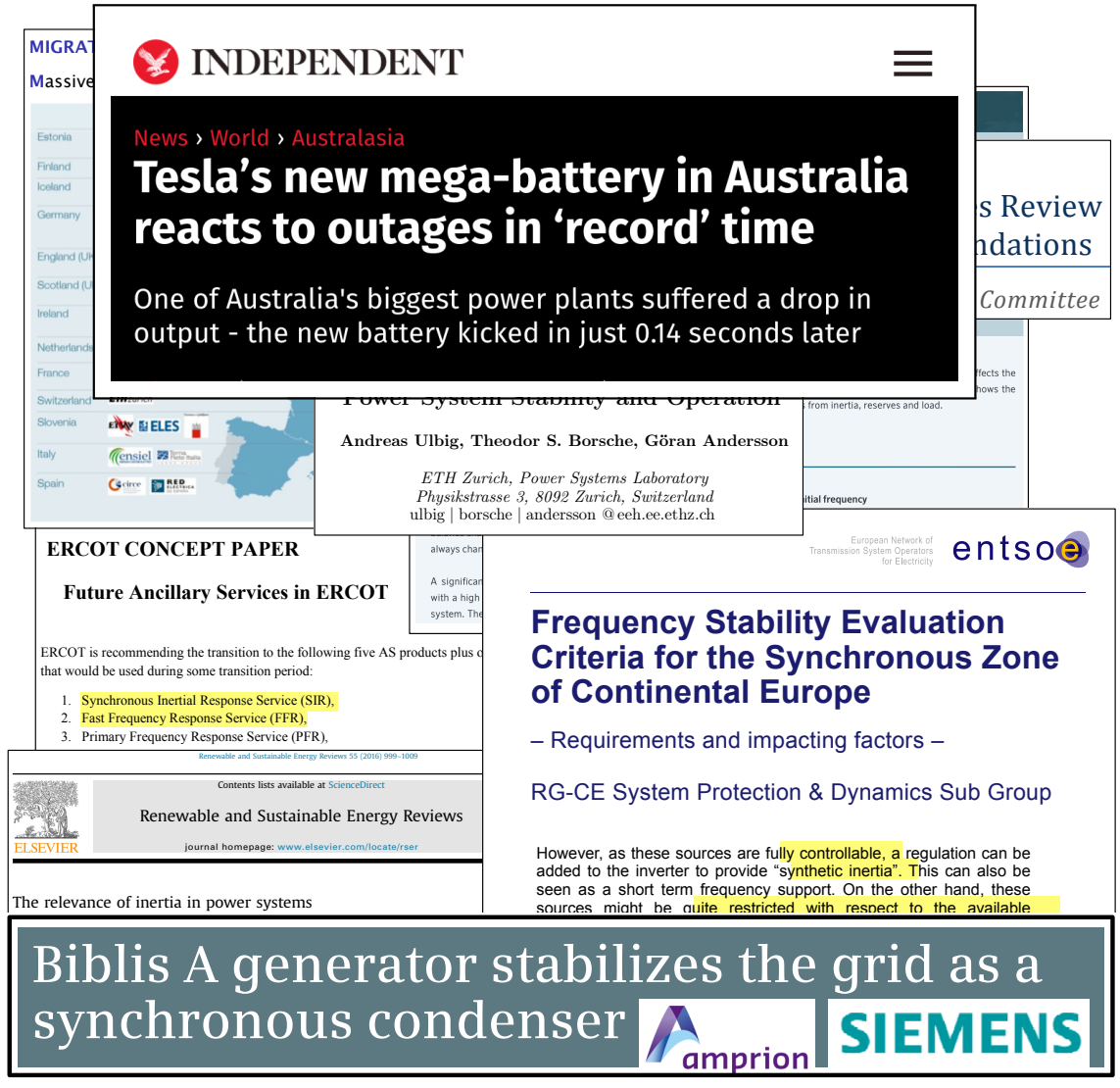
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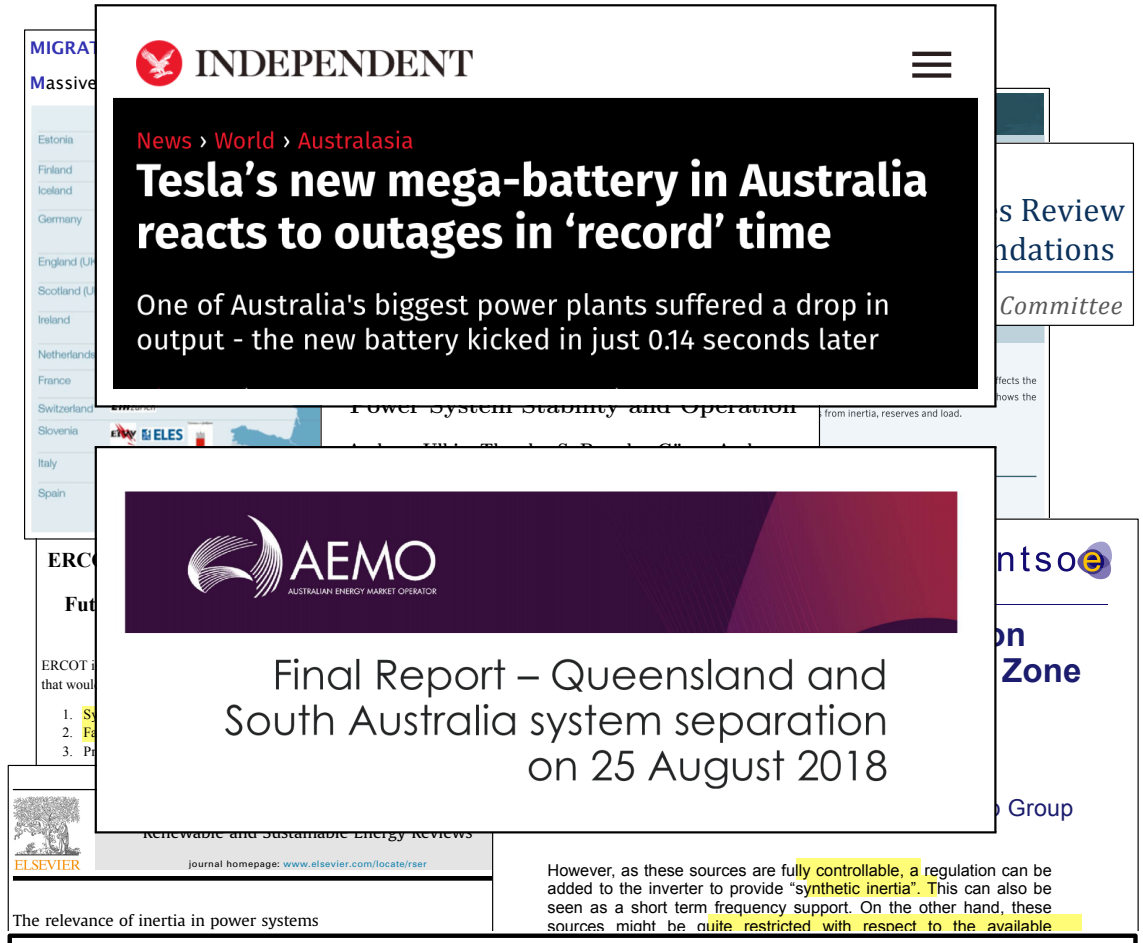
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obstacle to sustainability

- integrating power electronics
- robust & resilient control



Biblis A generator stabilizes the grid as a synchronous condenser

amprion SIEMENS

Critically re-visit modeling/analysis/control

Foundations and Challenges of Low-Inertia Systems

(Invited Paper)

Federico Milano
University College Dublin, Ireland
email: federico.milano@ucd.ie

Florian Dörfler and Gabriela Hug
ETH Zürich, Switzerland
emails: dorfler@ethz.ch, ghug@ethz.ch

David J. Hill* and Gregor Verbič
University of Sydney, Australia
* also University of Hong Kong
emails: dhill@eee.hku.hk, gregor.verbic@sydney.edu.au

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.

Critically re-visit modeling/analysis/control

Foundations and Challenges of Low-Inertia Systems

(Invited Paper)

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Florian Dörfler and Gabriela Hug
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emails: dorfler@ethz.ch, ghug@ethz.ch

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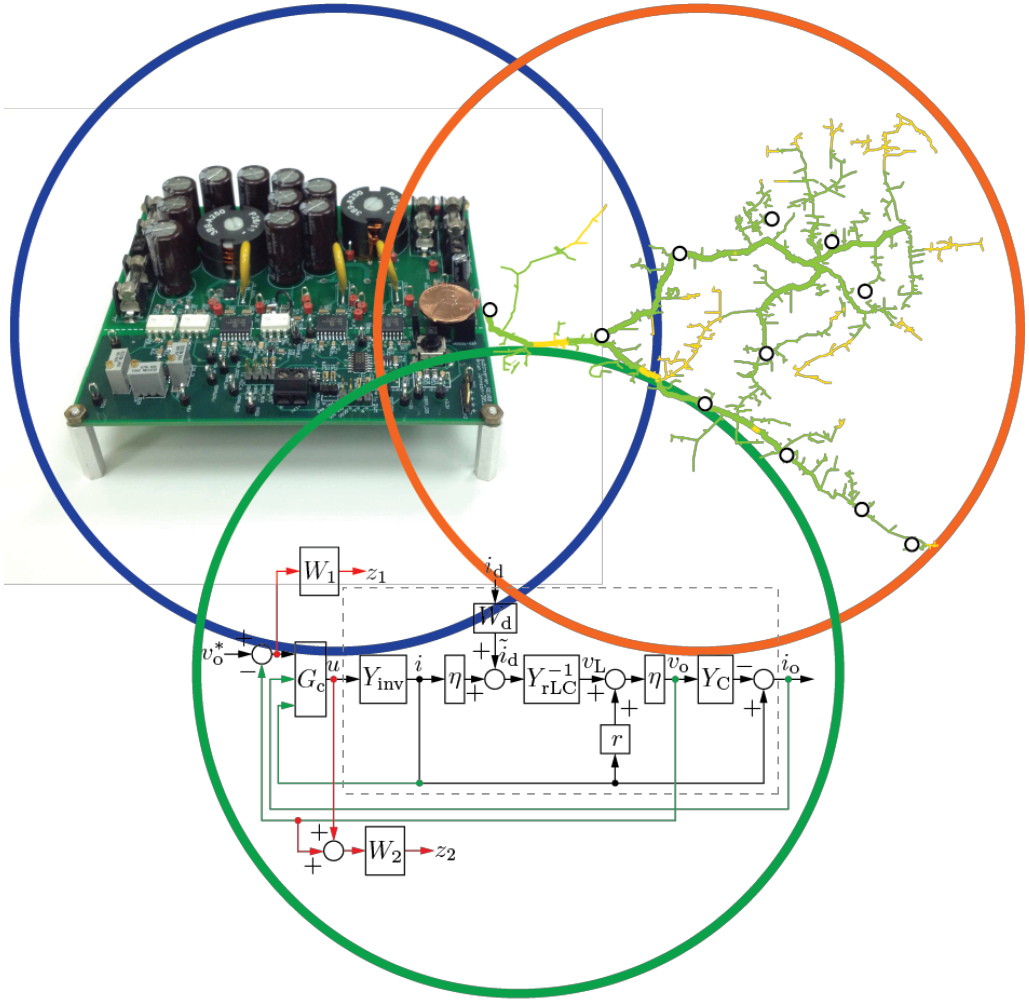
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a key unresolved challenge: control of power converters in low-inertia grids

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

Exciting research bridging communities

power electronics



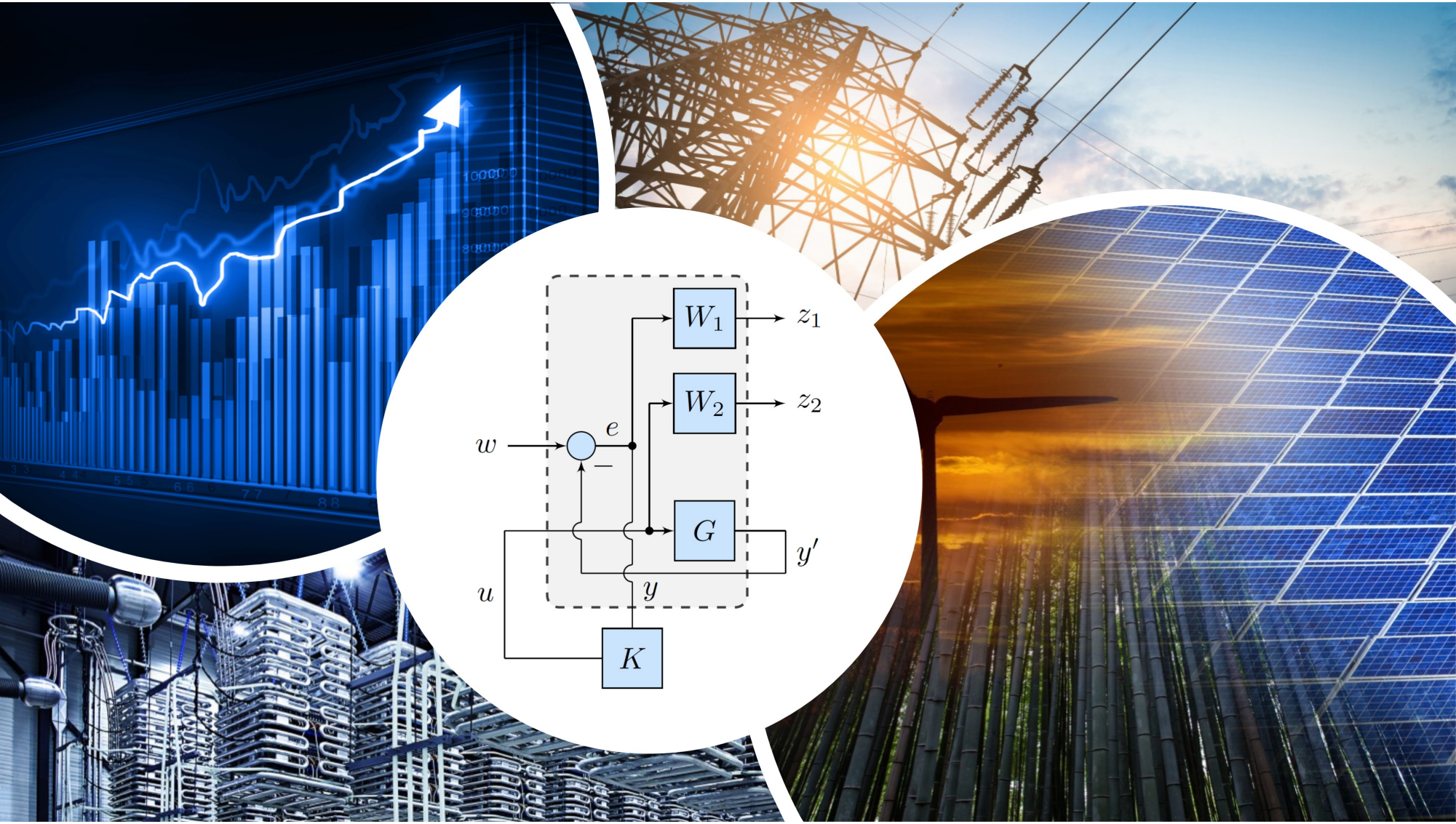
power systems

control systems

last figure was from a **power electronics** scientist (Brian Johnson)

next figure is from a **power systems** scientist (Uroš Marković)

Control is the *lingua franca* connecting . . .



Plenty of surveys from the power electronics / power systems perspective emphasizing **control !**

Understanding Stability of Low-Inertia Systems

Uros Markovic, *Student Member, IEEE,* Ognjen Stanojev, *Student Member, IEEE,* Petros Aristidou, *Member, IEEE,* Evangelos Vrettos, *Member, IEEE,* Duncan Callaway, *Senior Member, IEEE,* Gabriela Hug, *Senior Member, IEEE*

***Abstract*—Large-scale integration of renewable generation, usually interfaced to the network through power electronics, has led to an overall decrease in power system inertia. This paper presents novel insights into stability properties of such systems. For that purpose, a uniform set of Differential-Algebraic Equations (DAEs) describing a generic, low-inertia power system has been developed. A full-order, state-of-the-art control scheme of both synchronous and converter-based generators are included, with the latter differentiating between *grid-forming* and *grid-following* mode of operation. Furthermore, the dynamics of transmission lines and loads are captured in the model. Using modal analysis techniques such as participation factors and parameter sensitivity, the most vulnerable segments of the system are determined and the adverse effects of the underlying control interference are investigated. More precisely, this work characterizes the maximum permissible penetration levels of**

oversimplified generator control schemes, mostly due to the lack of a uniform state-space formulation for stability analyses. Moreover, the focus is primarily on distribution networks and microgrids, thus neglecting the potential impact of transmission line dynamics. An example that does incorporate line dynamics is [12], where the interactions between a virtual synchronous generator and a converter-interfaced load are investigated by considering small-signal stability under different operating conditions. While the authors include a dynamical model of the load and the interconnecting line, they analyze stability solely via parameter sweeps of the virtual inertia constant and load impedance, which does not provide enough insight into the nature of potential instabilities.

IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 55, NO. 6, NOVEMBER/DECEMBER 2019 7657

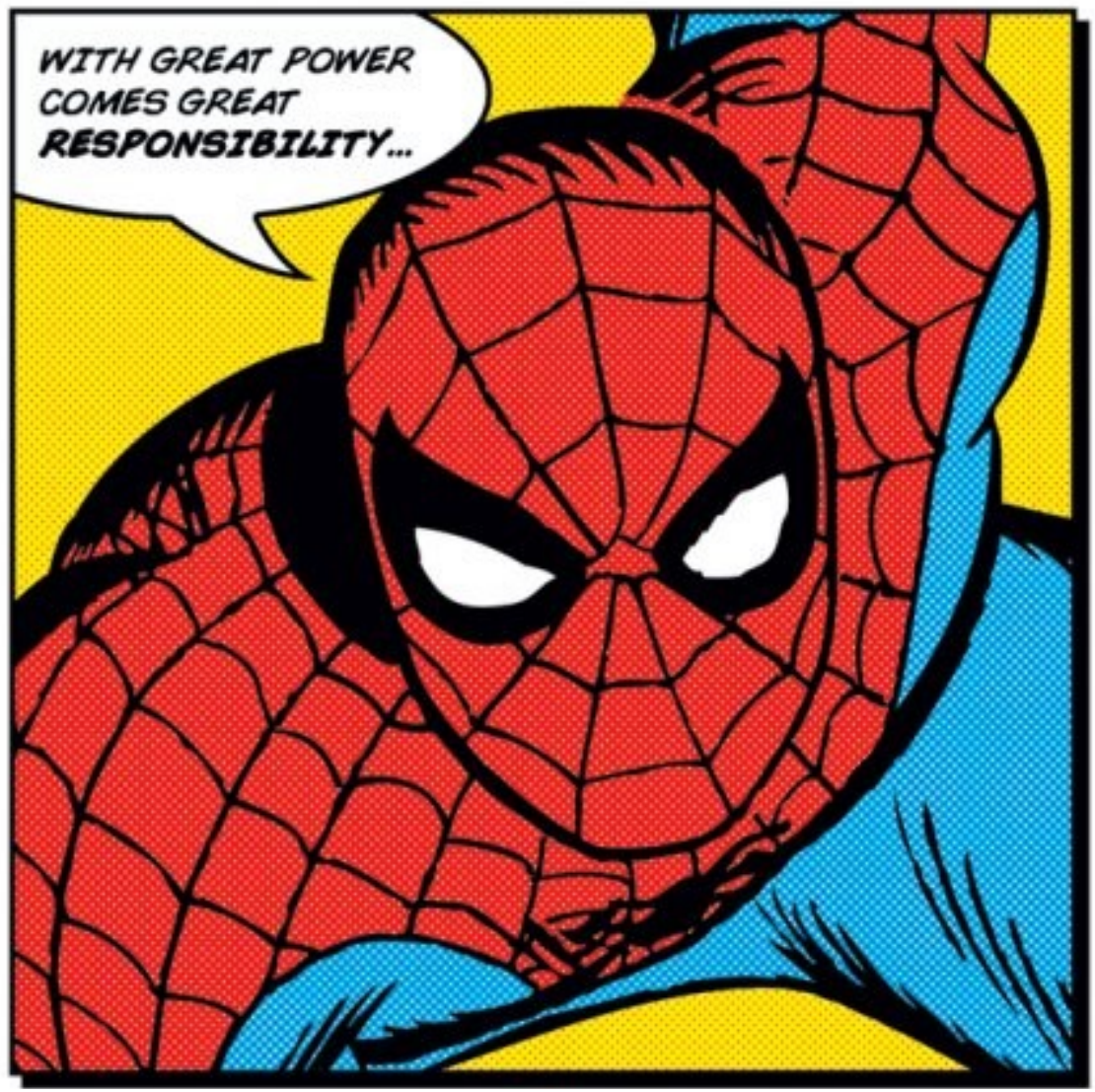
On the Stability of Power Electronics-Dominated Systems: Challenges and Potential Solutions

Qiao Peng, *Student Member, IEEE,* Qin Jiang, Yongheng Yang, *Senior Member, IEEE,* Tianqi Liu, *Senior Member, IEEE,* Huai Wang, *Senior Member, IEEE,* and Frede Blaabjerg, *Fellow, IEEE*

***Abstract*—The modern power system is becoming more complicated due to the ever increasing penetration of power electronics, which is referred to as a power-electronics-dominated system (PEDS). In this case, the analysis, control, and operation of the entire power system should tone with the energy-paradigm transition pace, where the challenges should be properly tackled. After the brief introduction of grid-connected converters, this article explores stability challenges of PEDSs, especially on the low inertia issue and multitimescale characteristics, as well as the dynamics when connected to weak grids. The low inertia issue is considered as one of great challenges that power electronics introduce to the**

FSM	Frequency sensitive mode.
IR	Inertia response.
LCC	Line-commutated converter.
LCC-HVDC	LCC-based high voltage direct current.
MIESCR	Multiinfeed interactive effective short-circuit ratio.
MIIF	Multiinfeed interaction factor.
MPC	Model predictive control.
MPP	Maximum power point.

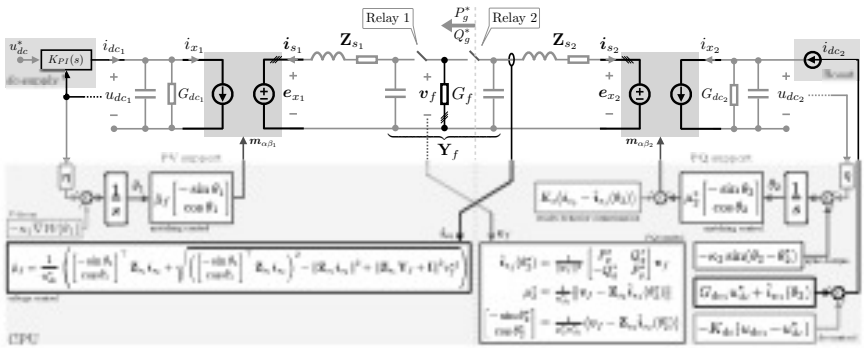
Conclusion: unique opportunity for control

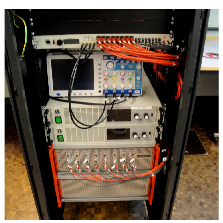


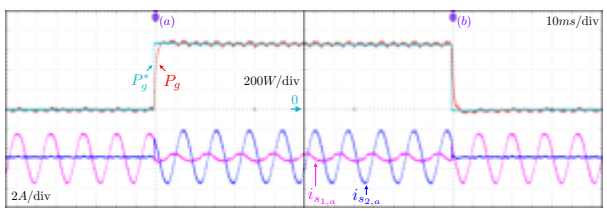
Personal view on the field & agenda

device-level (power electronics)

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



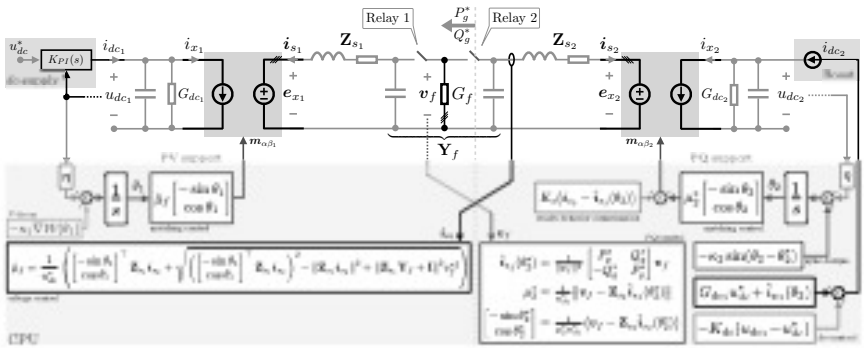


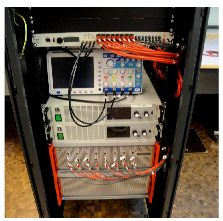


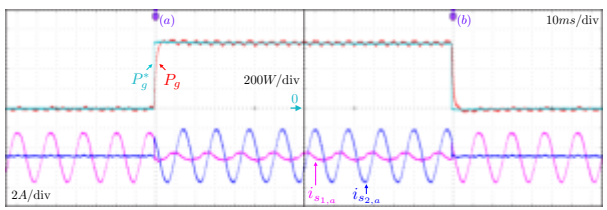
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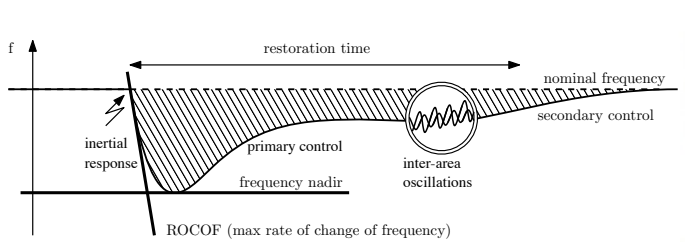


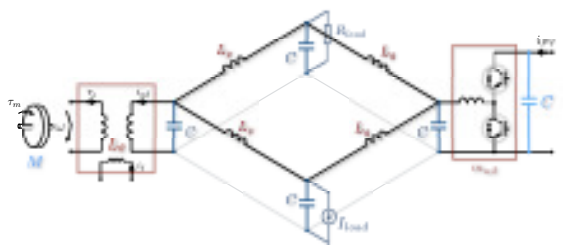


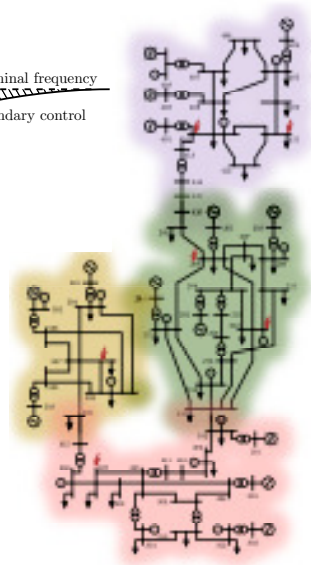


system-level (low-inertia grid)

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



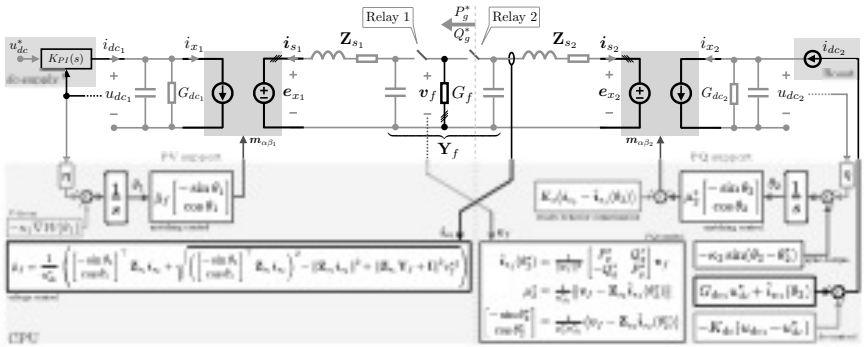


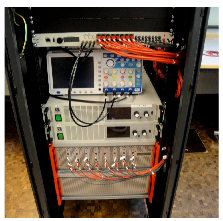


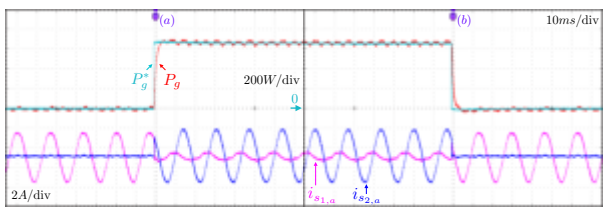
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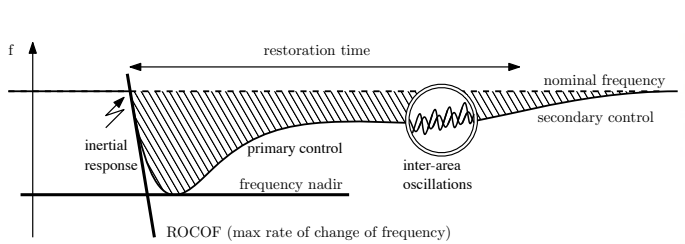


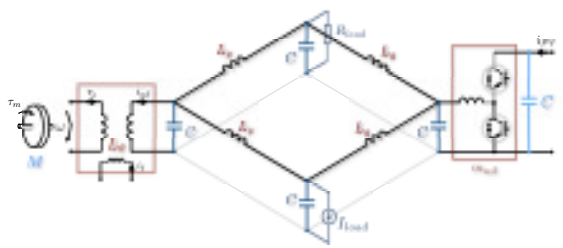


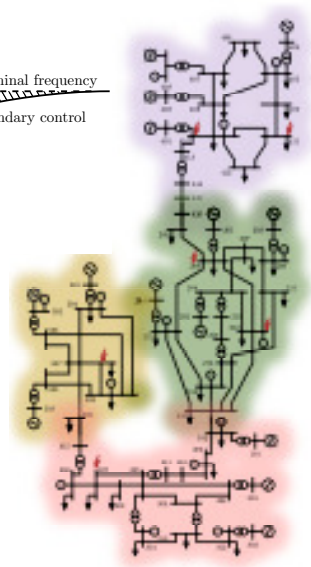


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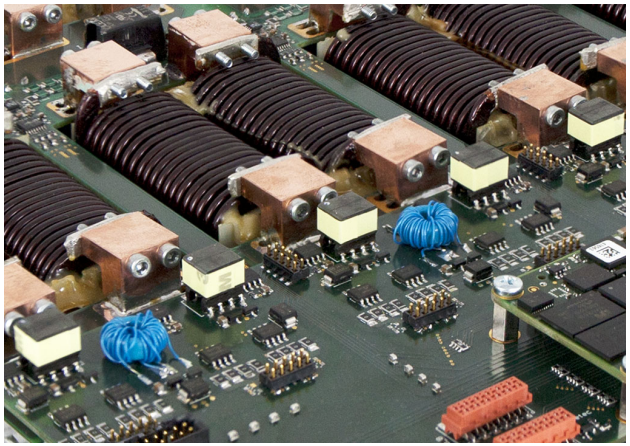


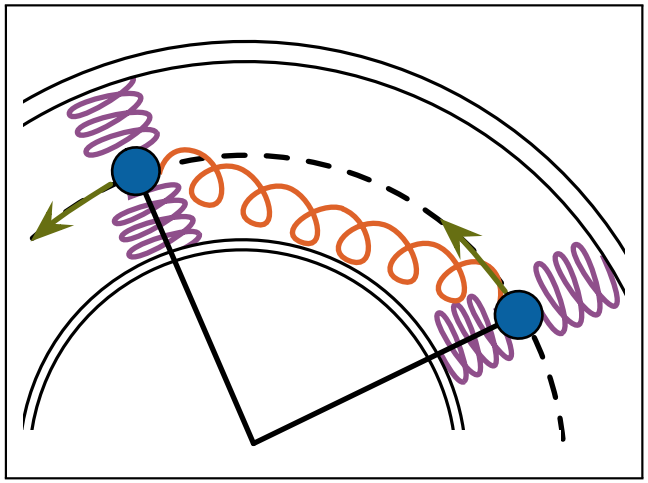


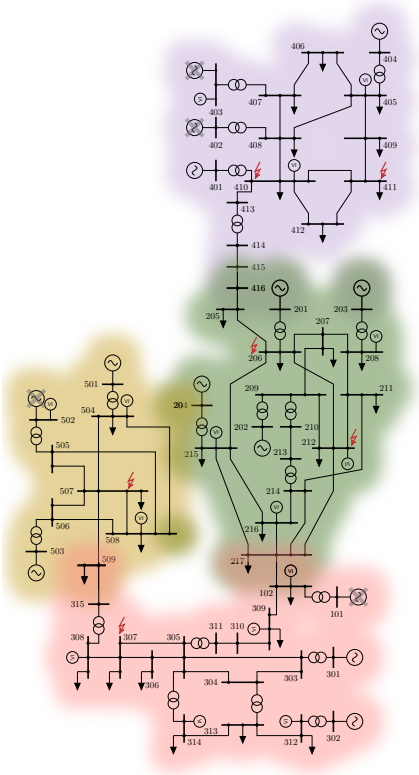


theory ↔ practice | device ↔ system | proof ↔ experiment

Focus of today's tutorial







modeling, control specifications, & game changers

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

decentralized control of power converters

- hierarchical control architectures & grid-forming vs. grid-following
- grid-forming controls: VSM, droop, matching, & VOC

effect of local controls in large-scale systems

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

Main look-up reference for this part

up to some $\pm$ sign conventions

Control of Low-Inertia Power Systems

Florian Dörfler[1] and Dominic Groß[2]

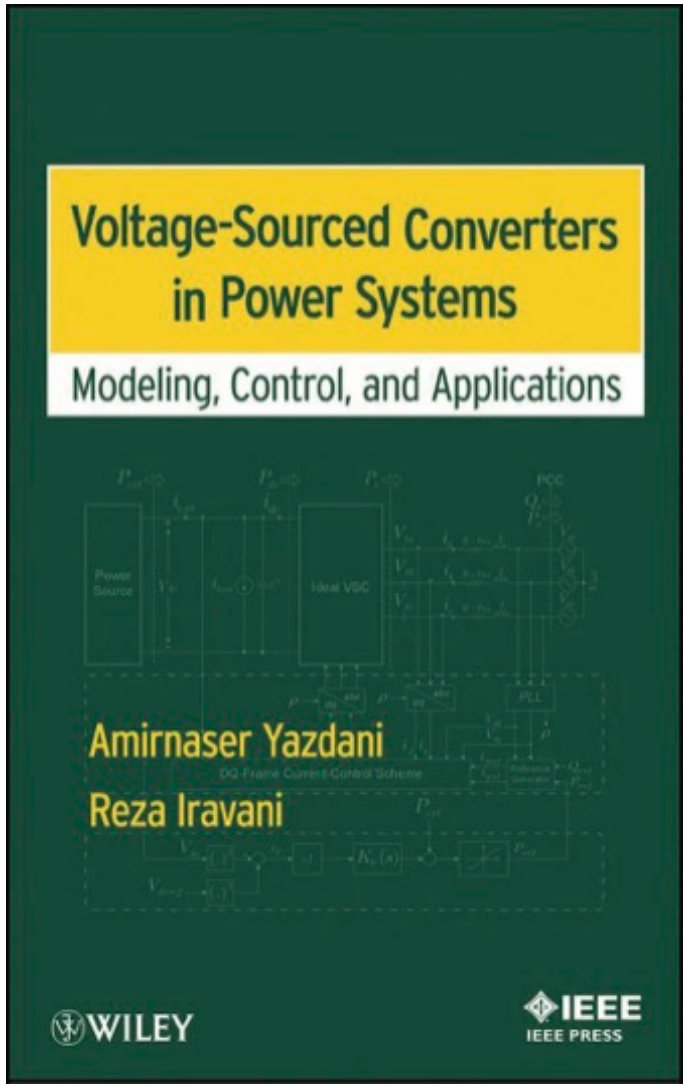
[1]Automatic Control Laboratory, ETH Zurich, Zurich, Switzerland, 8092; email: dorfler@ethz.ch
[2]Electrical and Computer Engineering, University of Wisconsin-Madison, Madison, United States, WI 53706; email: dominic.gross@wisc.edu

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modeling,
control specifications,
& game changers

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

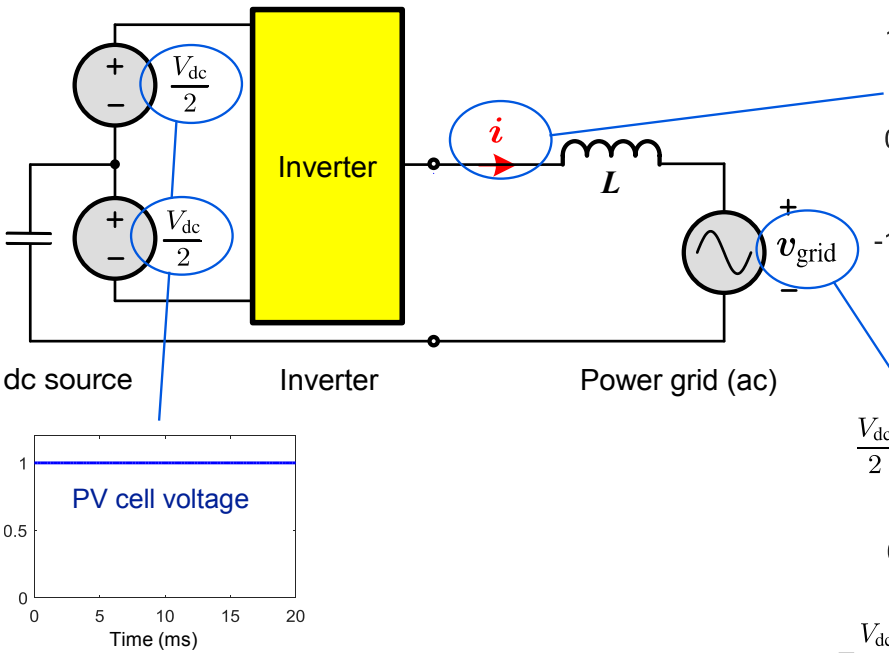


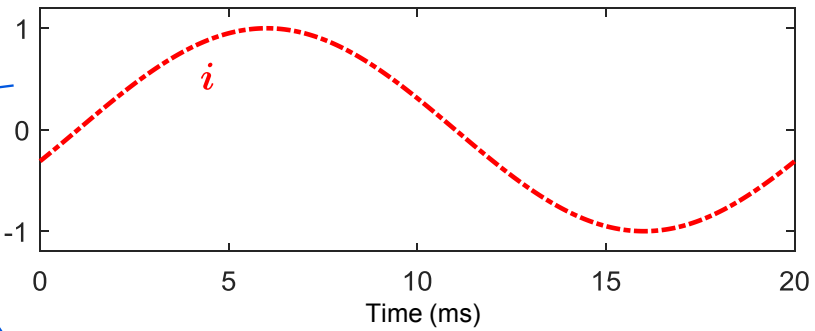
Power electronics dc/ac conversion basics

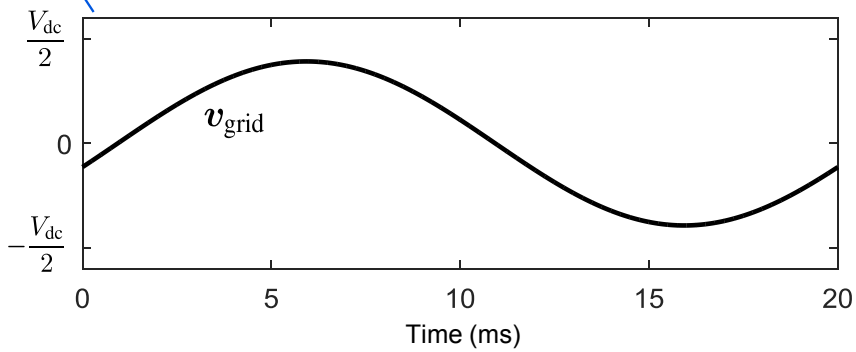
adapted from slides by Tobias Geyer (ABB & ETH Zürich)

abstract dc-to-ac power conversion

objective: transfer power to the grid





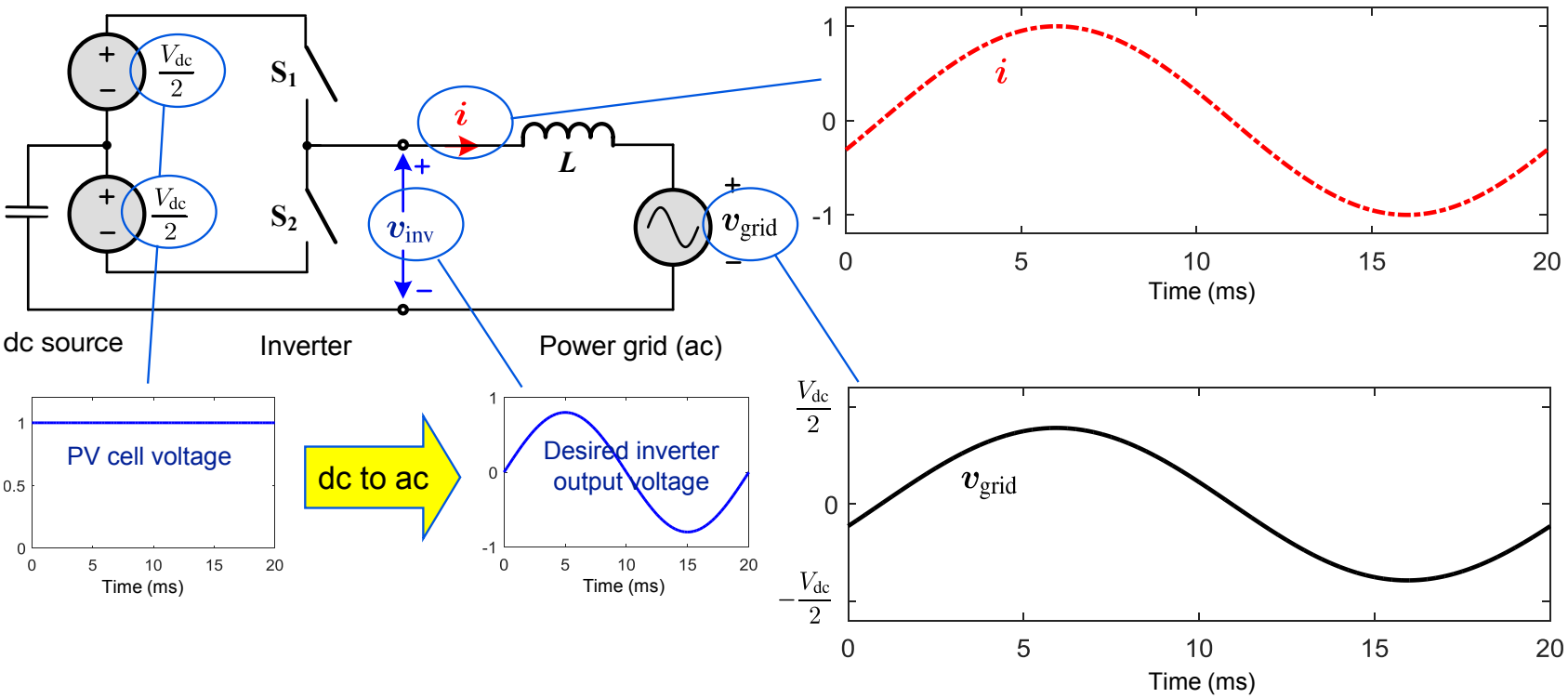


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2-level inverter with idealized switches

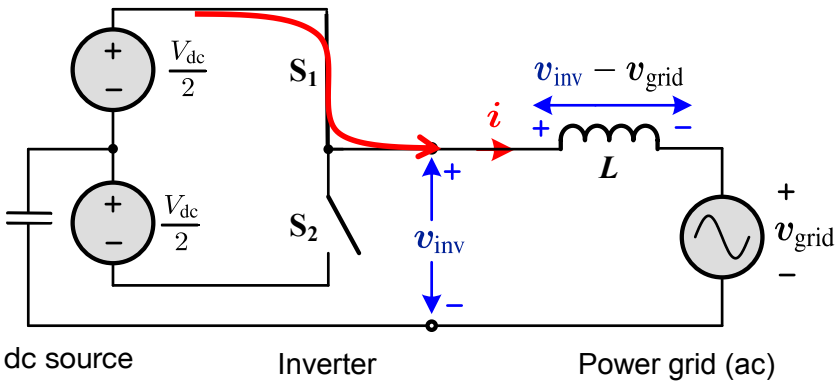
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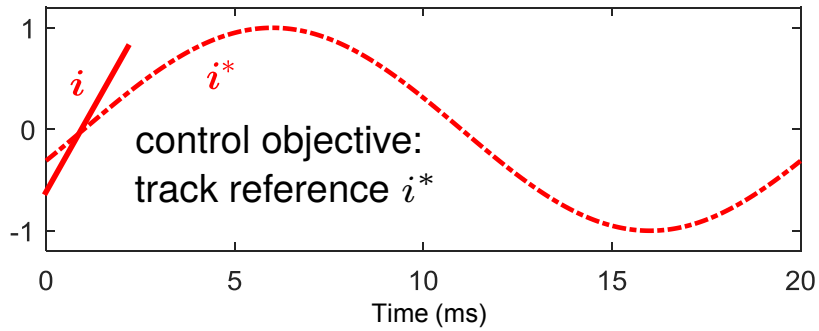
The switches are operated dually:

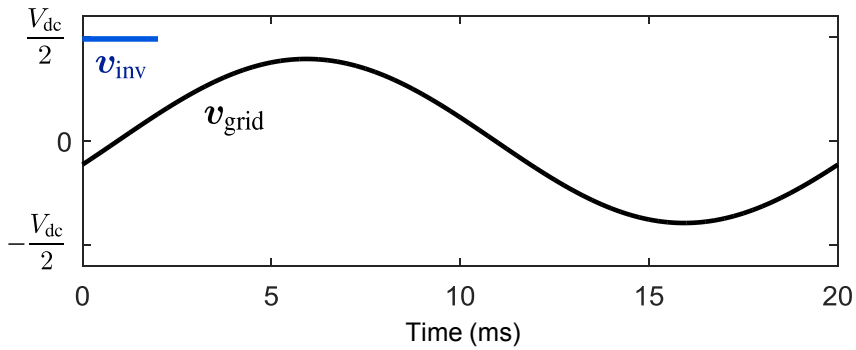
- S_1 on and S_2 off: $v_{inv} = V_{dc}/2$

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

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

objective: transfer power to the grid

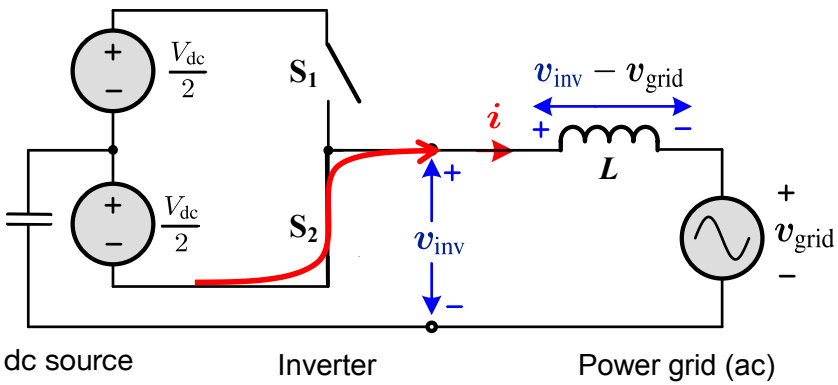




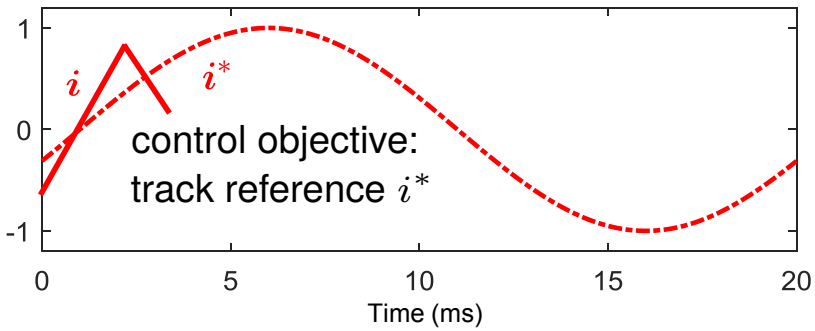
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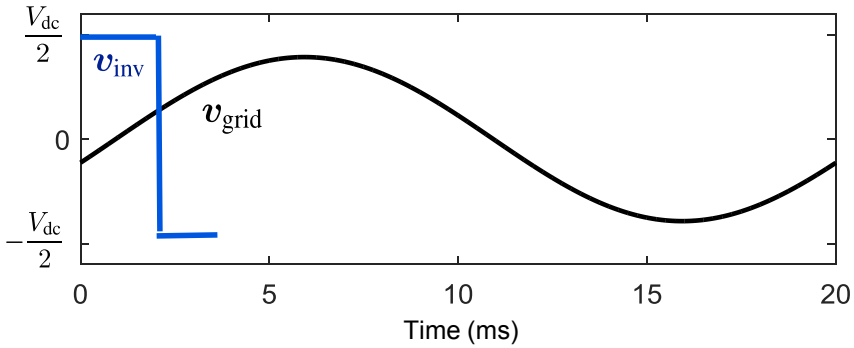
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2-level inverter with idealized switches



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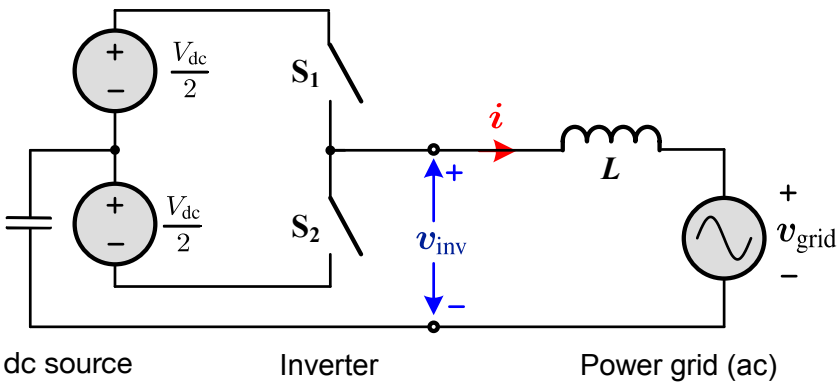
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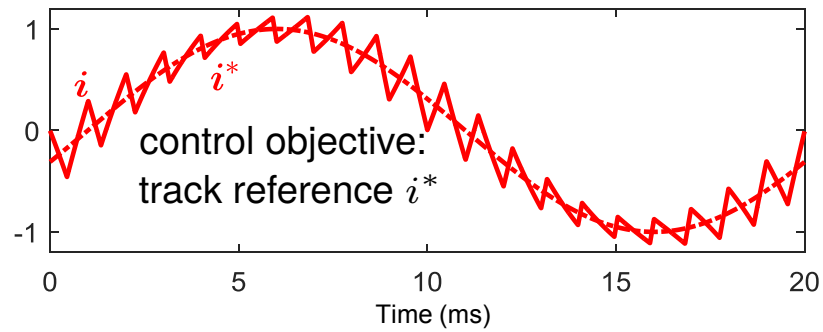
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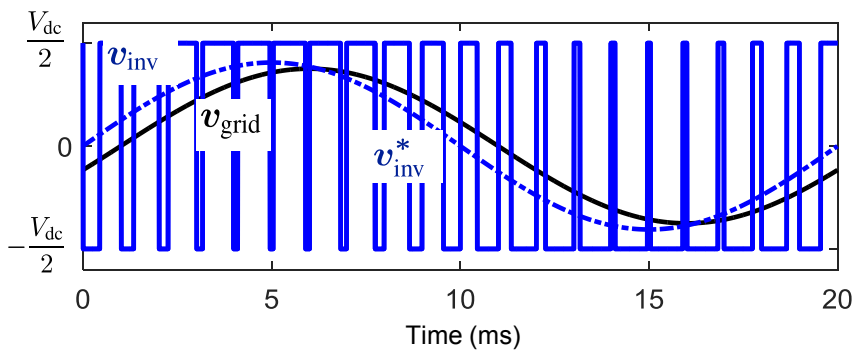
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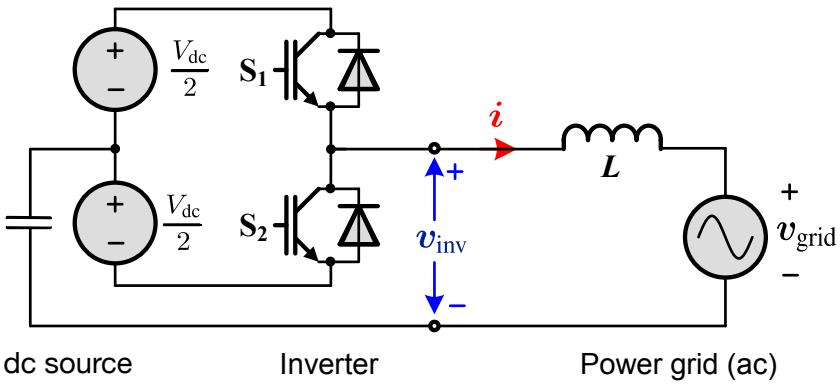
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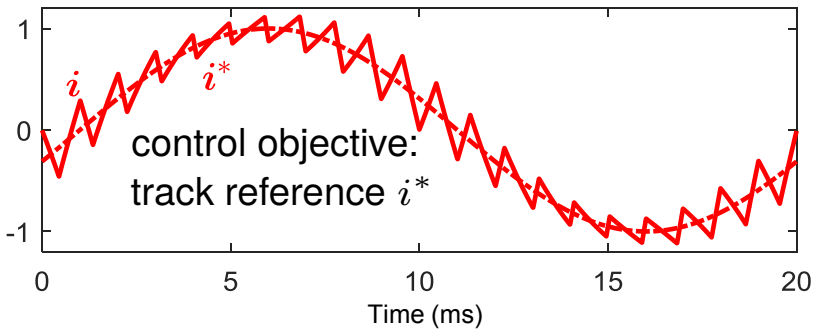
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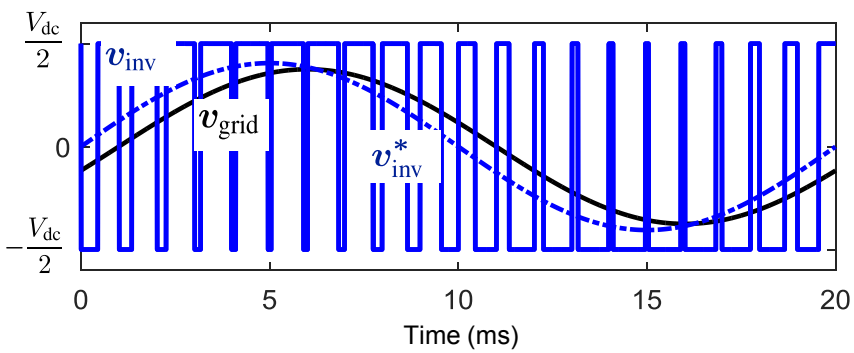
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inverter with semi-conductor switches



objective: transfer power to the grid





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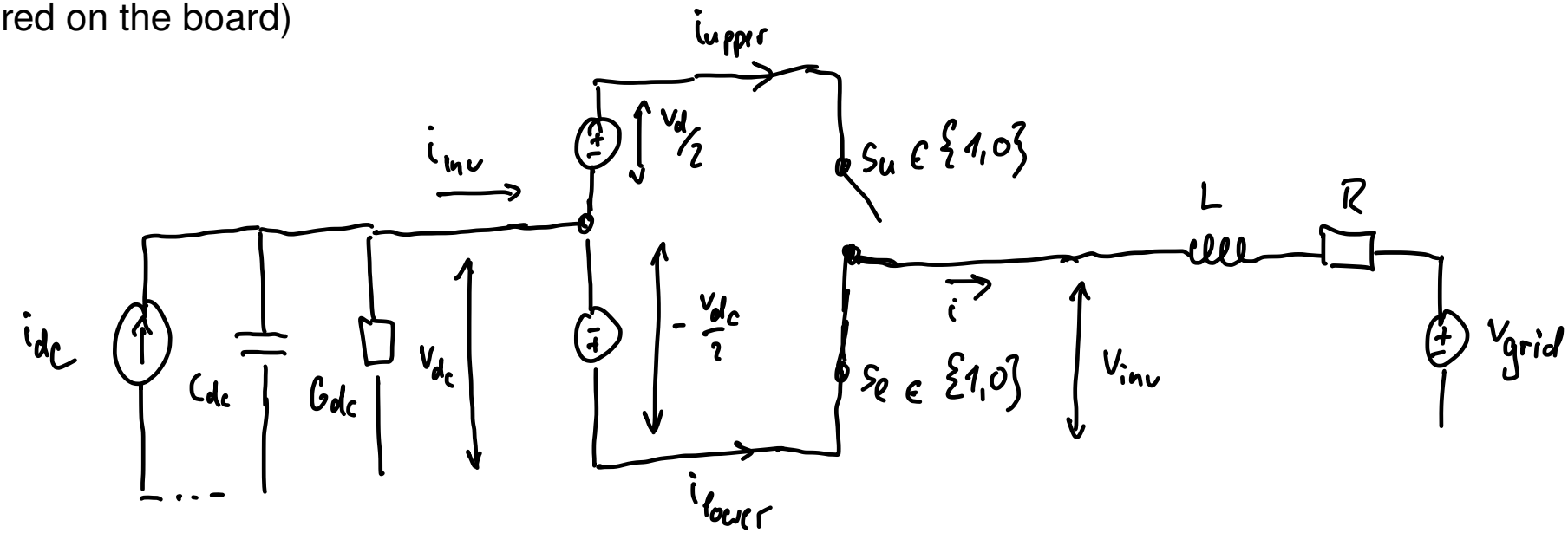
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- "on average" & "nearly smooth" can be made mathematically
  precise by **averaging theory** (see board for details)

Average-switch modeling of converters

(covered on the board)



switched model:

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

$$L\,\dot{i} = -R\,i + v_{inv} - v_{grid}$$

where

$$i_{inv} = i_{upper} + i_{lower}$$

$$v_{inv} = \frac{v_{dc}}{2}\cdot(s_{upper} - s_{lower})$$

$$s_u + s_l = 1 \quad , \; s_u, s_l \in \{0, 1\}$$

power balance:

$$P_{dc} = v_{dc}\cdot i_{inv} =$$

$$v_{inv}\cdot i = P_{ac}$$

Averaging: (ac-side focus)

assume: v_{inv} is a T-periodic (due to switching)

$$\Rightarrow \bar{v}_{inv} = \frac{1}{T}\int_0^T v_{inv}(\tau)\,d\tau$$

higher-order Fourier terms $\longrightarrow$ $\tilde{v}_{inv} + \sum_{k=1}^{\infty} a_k \cos\left(\frac{2\pi}{T}\cdot k\cdot t\right) + b_k \sin\left(\frac{2\pi}{T}\cdot k\cdot t\right)$

current: write ac current as a superposition: $i = \bar{i} + \tilde{i}$

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

$$L\dot{\bar{i}} = -R\bar{i} + \bar{v}_{inv} - v_{grid}$$ ← assume v_{grid} is periodic

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

$$L\dot{\tilde{i}} = -R\tilde{i} + \text{"Fourier series"}$$

low-pass filter with cut-off frequency R/L

"harmonics of frequencies $\frac{2\pi}{T}\cdot k$ for $k \in \{1, 2, \dots\}$"

all conclusion hold with $\mathcal{O}(1/T)$

if $R/L \ll \frac{2\pi}{T}$ (high switching frequency) then $\tilde{i} = 0$

⇝ apply averaging to all signals and drop the higher harmonics

$$L\dot{\bar{i}} = -R\bar{i} + \bar{v}_{inv} - v_{grid}$$

$\bar{s}_u + \bar{s}_e = 1$

$$L\frac{v_{dc}}{2}(\bar{s}_u - \bar{s}_e) = \frac{v_{dc}}{2}(2\bar{s}_u - 1)$$

$$= v_{dc}(\bar{s}_u - 1/2)$$

$\bar{s}_u$: $m \in [-1/2, +1/2]$ modulation (cont. control signal after averaging)

$$\Rightarrow \boxed{L\dot{\bar{i}} = -R\bar{i} + m v_{dc} - v_{grid}}$$

averaged model

Back to the dc dynamics: $C_{dc}\dot{v}_{dc} + G_{dc}v_{dc} = i_{dc} - \bar{i}_{inv} = i_{dc} - m\bar{i}$

power balance: $\bar{i}_{inv} \cdot v_{dc} = \bar{v}_{inv} \cdot \bar{i}$

$= m v_{dc} \cdot \bar{i}$

$$\boxed{C_{dc}\dot{v}_{dc} = -G_{dc}v_{dc} + i_{dc} - m\bar{i}}$$

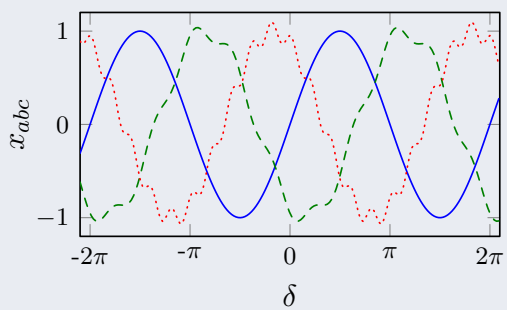
Modeling review: signal space in 3-phase

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

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



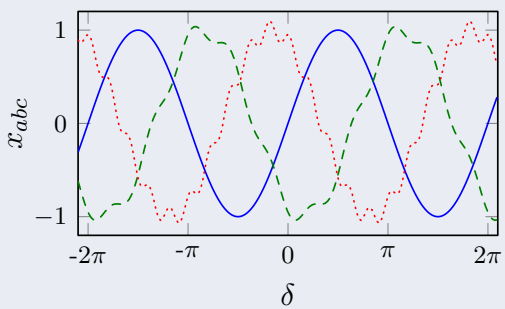
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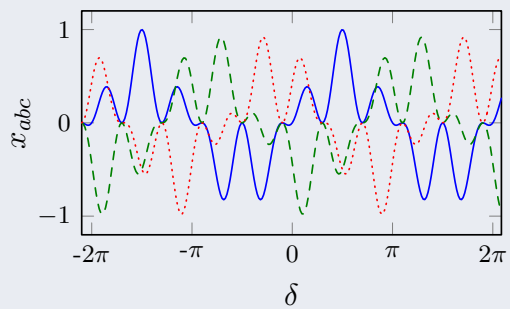


balanced (nearly true)

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

so that

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



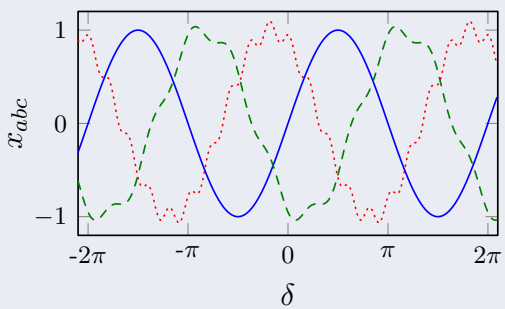
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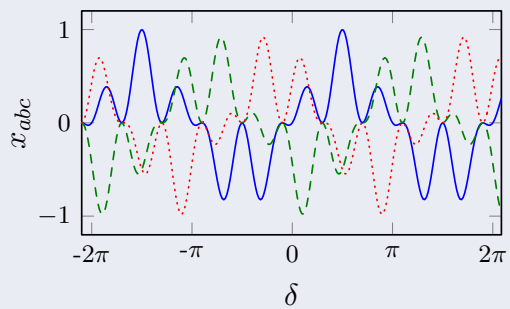


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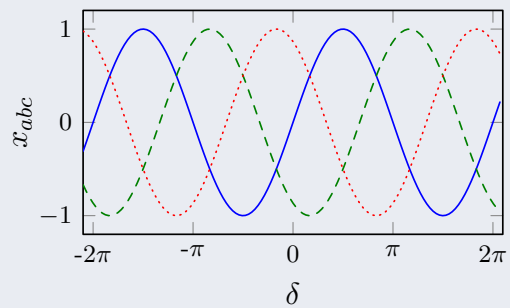


synchronous (desired)

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

const. freq & amp

$\Rightarrow$ const. in rot. frame



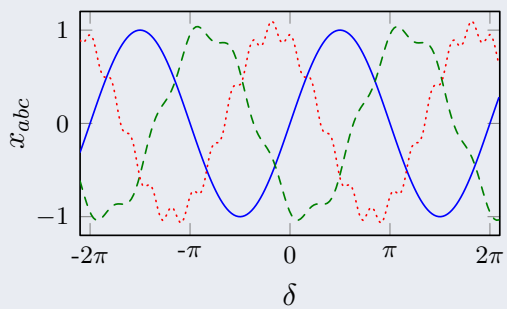
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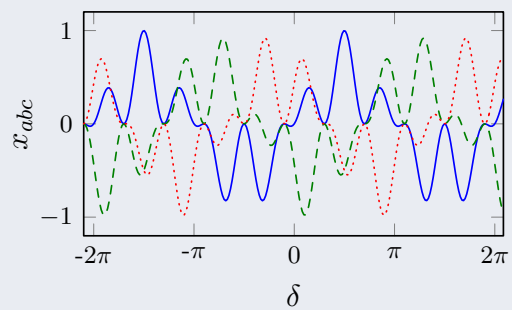


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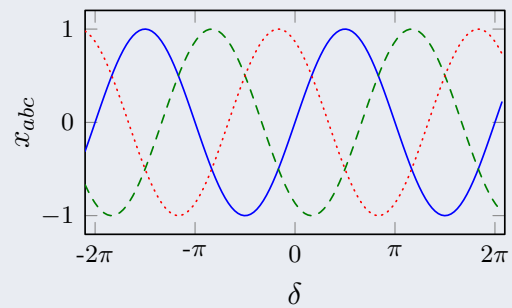


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assumption: balanced $\Rightarrow$ 2d-coordinates $x(t) = [x_\alpha(t)\, x_\beta(t)]$ or $x(t) = A(t)\mathrm{e}^{\mathrm{i}\delta(t)}$

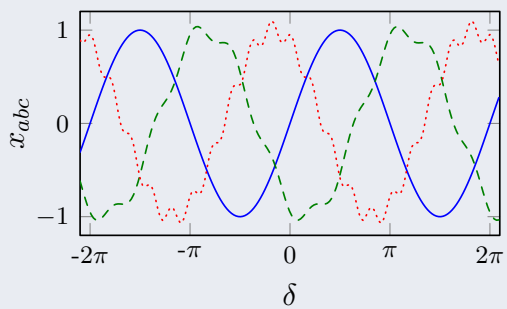
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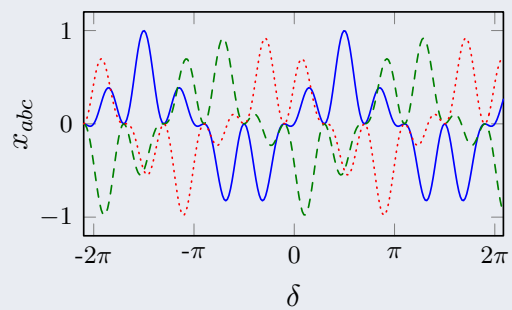


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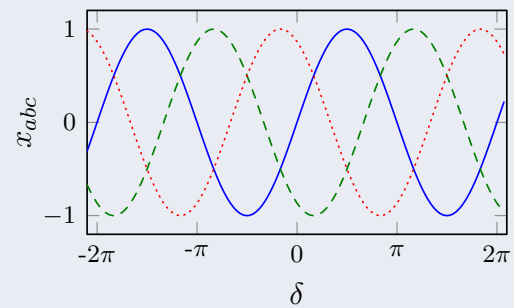


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current/voltage $\rightarrow$ power: active $p = v^\top i$ and reactive $q = v^T \left[\begin{smallmatrix} 0 & -1 \\ 1 & 0 \end{smallmatrix}\right] i = v \times i$

Modeling: voltage source converter

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

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

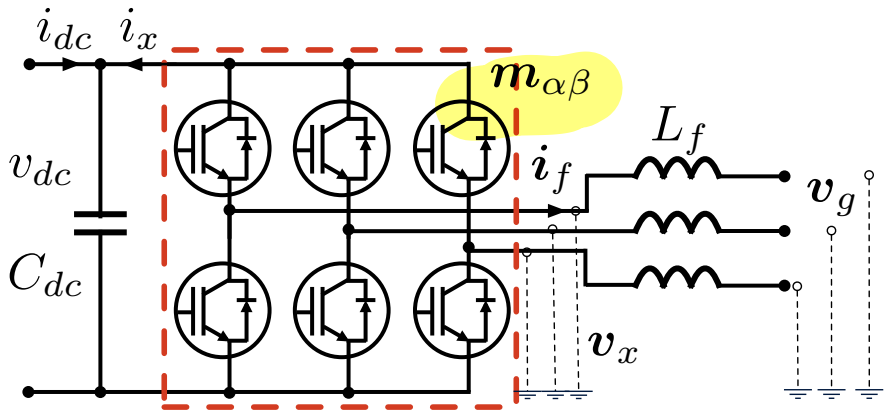
3. **power electronics modulation**

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

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

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

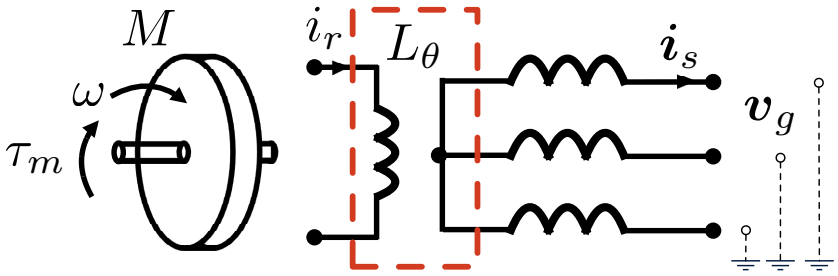
5. connection to grid with voltage $\boldsymbol{v}_g$



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

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

Modeling review: synchronous generator



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

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

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

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

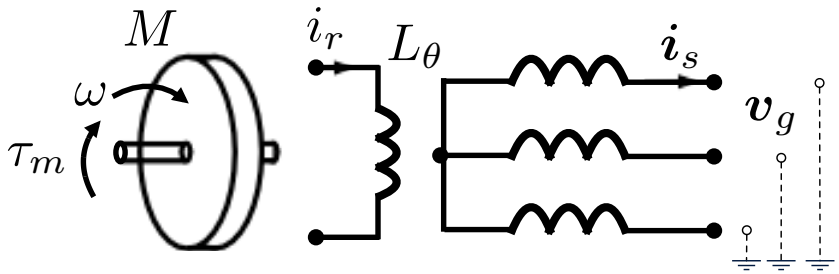
$$L_\theta = \begin{bmatrix} L_\mathsf{s} & 0 & L_\mathsf{m}\cos\theta \\ 0 & L_\mathsf{s} & L_\mathsf{m}\sin\theta \\ L_\mathsf{m}\cos\theta & L_\mathsf{m}\sin\theta & L_\mathsf{r} \end{bmatrix}$$

   (neglected i_r rotor current dynamics)

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

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

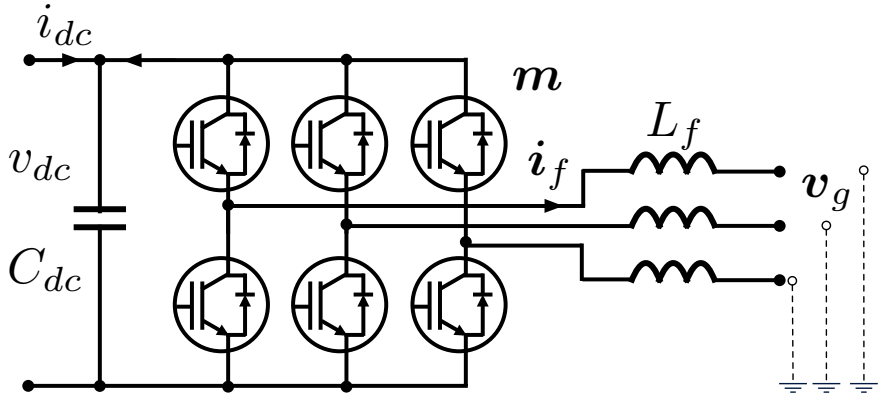
Comparison: conversion mechanisms



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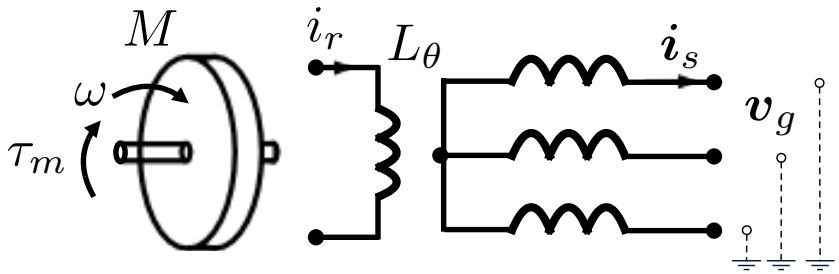
$$L_\mathsf{s}\frac{\mathrm{d}\boldsymbol{i}_s}{\mathrm{d}t} = -R_s\boldsymbol{i}_s + \boldsymbol{v}_g - L_\mathsf{m} i_r \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix}\omega$$



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

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

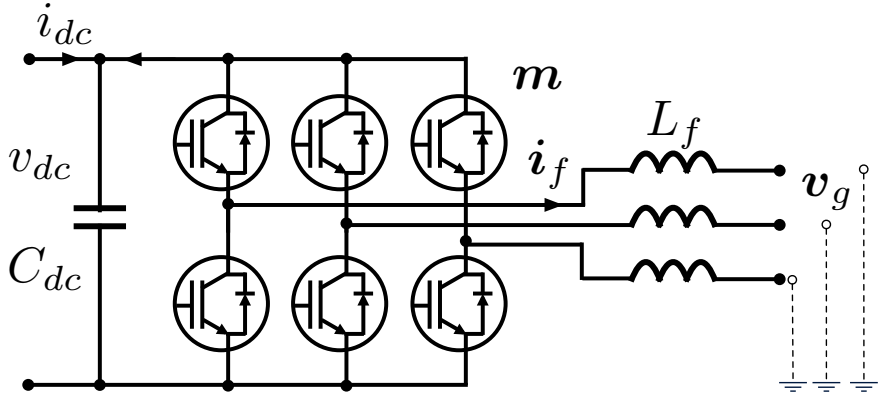
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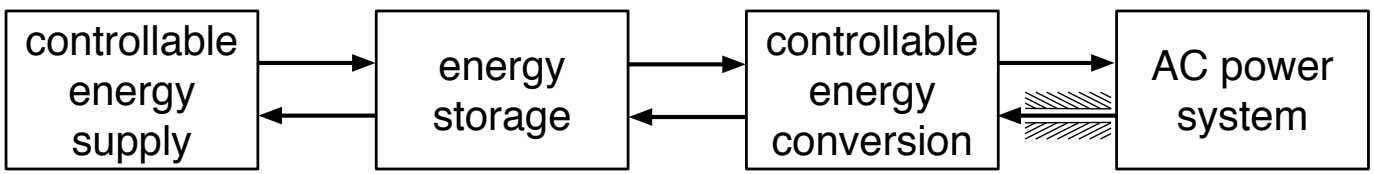
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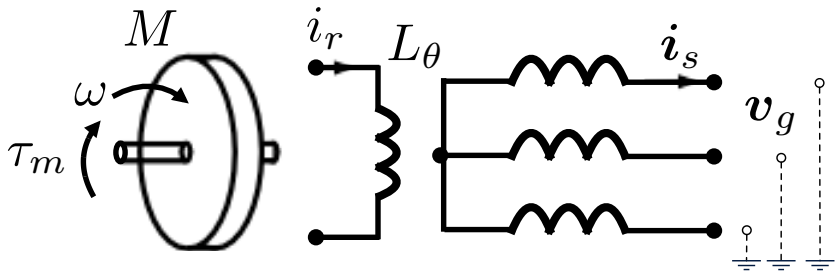
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τ_m (slow)	M (large)	L_θ (physical)	resilient
vs.	vs.	vs.	vs.
i_dc (fast)	C_dc (small)	$\boldsymbol{m}$ (control)	fragile (over-currents)

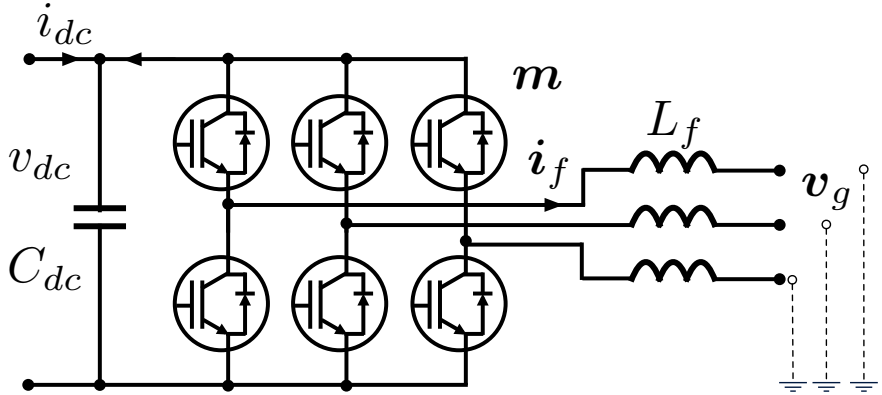
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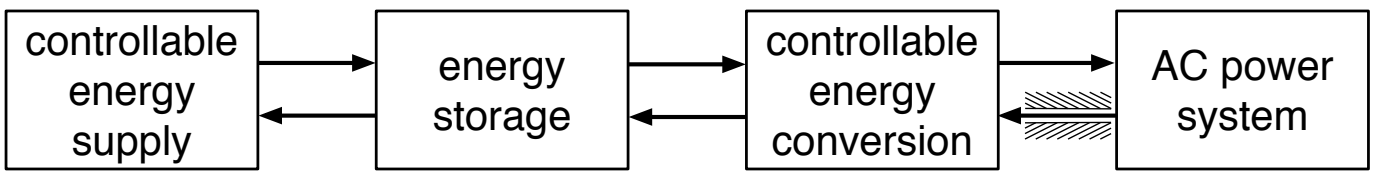
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τ_m (slow) vs. i_dc (fast)	M (large) vs. C_dc (small)	L_θ (physical) vs. $\boldsymbol{m}$ (control)	resilient vs. fragile (over-currents)

physical & robust
vs.
controlled & agile
signal/energy transformer
+ (kinetic) **storage**

Energy-based modeling & insights

(covered on the board)

model (averaged):

$$C_{dc}\,\dot{v}_{dc} = -G_{dc}\,v_{dc} + i_{dc} + m^T i_f$$

$$L_f\,\dot{i}_f = -R_f i - v_g + m\,v_{dc}$$

↳ $q = C_{dc} v_{dc}$

$\lambda = L_f i_f$

Hamiltonian: $H(q,\lambda) = \frac{1}{2} q^2/C_{dc} + \frac{1}{2}\lambda^2/L_f$

$= \frac{1}{2} C_{dc} v_{dc}^2 + \frac{1}{2} L_f i_f^2$ ~ small

dynamics:

$$\begin{bmatrix}\dot{q}\\ \dot{\lambda}\end{bmatrix} = \left(\begin{bmatrix} 0 & +m \\ +m & 0\end{bmatrix} - \begin{bmatrix} +G_{dc} & 0 \\ 0 & +R_f\end{bmatrix}\right)\cdot \nabla H + \begin{bmatrix} i_{dc} \\ v_g\end{bmatrix}$$

lossless conversion; losses

power balance:

$$\dot{H} = \nabla H^T \begin{bmatrix} 0 & +m \\ -m & 0\end{bmatrix} \nabla H - \nabla H^T \begin{bmatrix} G_{dc} & 0 \\ 0 & R_f\end{bmatrix} \nabla H$$

0; dissipation

$$v_{dc}\cdot i_{dc} + i^T v_g$$

fast; power supply; fragile

Synchronous machine: $H = \frac{1}{2} p^2 \Pi^T + \frac{1}{2} \lambda^T L(\theta) \lambda$

$\dot{H} = 0 - \nabla H^T \begin{bmatrix} D & \\ & R_s \end{bmatrix} \nabla H + \omega \cdot \tau_m + i_s^T v_s$

0 — lossless conversion

dissipation

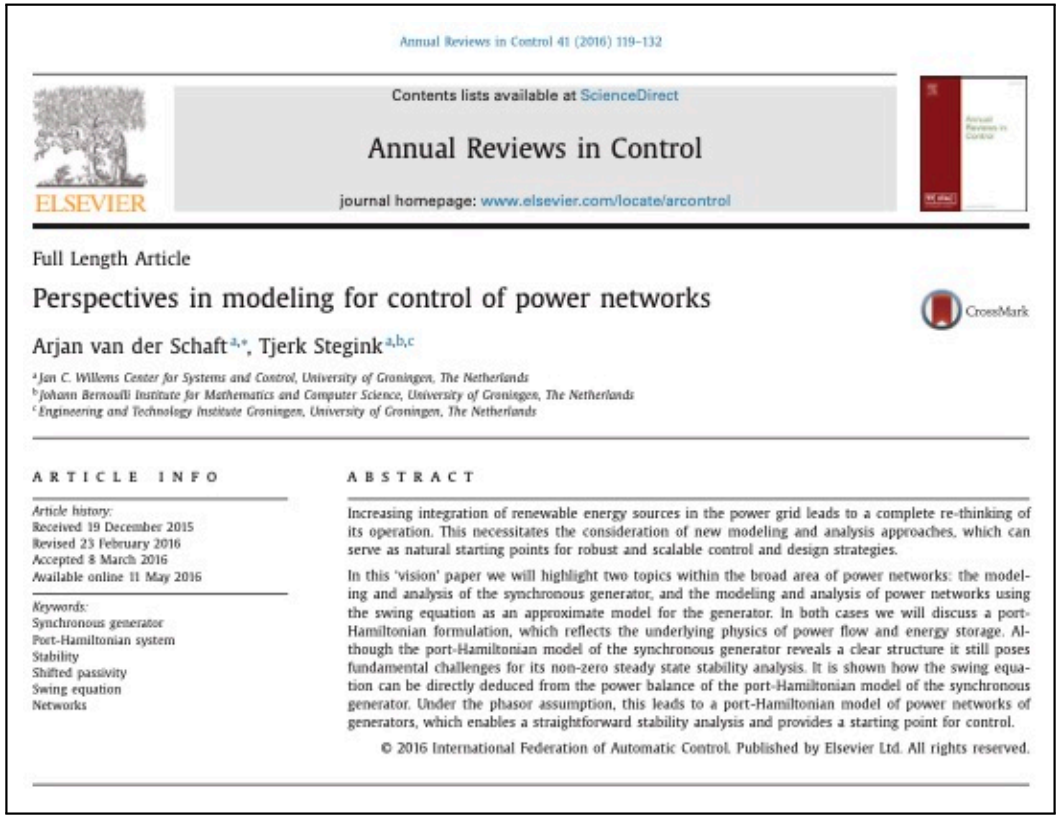
supply

slow

robust

large

Great tutorial on energy-based modeling
$\rightarrow$ basis for energy-based control design



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Full Length Article

Perspectives in modeling for control of power networks

Arjan van der Schaft[a,*], Tjerk Stegink[a,b,c]

[a] Jan C. Willems Center for Systems and Control, University of Groningen, The Netherlands
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[c] Engineering and Technology Institute Groningen, University of Groningen, The Netherlands

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Swing equation
Networks

ABSTRACT

Increasing integration of renewable energy sources in the power grid leads to a complete re-thinking of its operation. This necessitates the consideration of new modeling and analysis approaches, which can serve as natural starting points for robust and scalable control and design strategies.

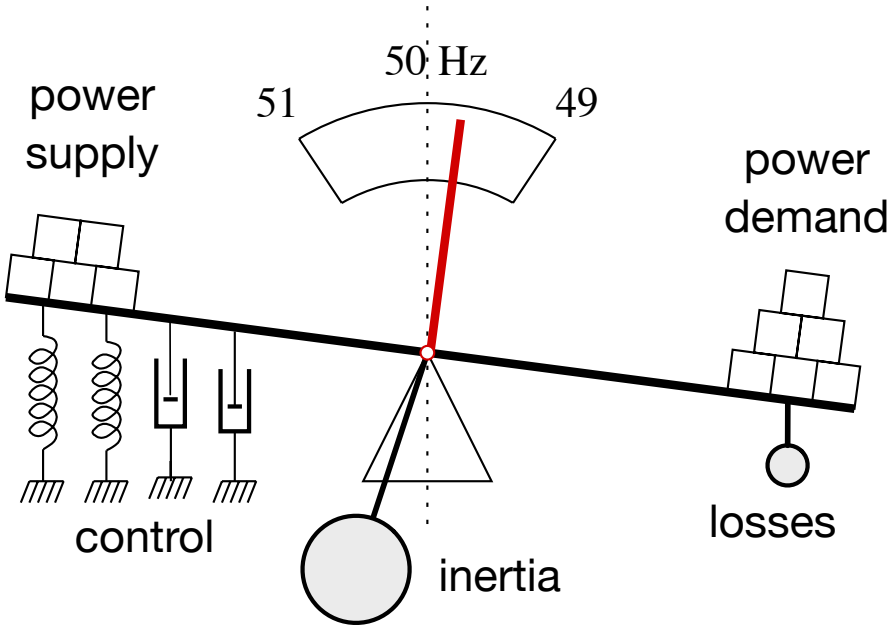
In this 'vision' paper we will highlight two topics within the broad area of power networks: the modeling and analysis of the synchronous generator, and the modeling and analysis of power networks using the swing equation as an approximate model for the generator. In both cases we will discuss a port-Hamiltonian formulation, which reflects the underlying physics of power flow and energy storage. Although the port-Hamiltonian model of the synchronous generator reveals a clear structure it still poses fundamental challenges for its non-zero steady state stability analysis. It is shown how the swing equation can be directly deduced from the power balance of the port-Hamiltonian model of the synchronous generator. Under the phasor assumption, this leads to a port-Hamiltonian model of power networks of generators, which enables a straightforward stability analysis and provides a starting point for control.

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see also the tutorials/surveys of Ortega, Scherpen, v.d. Schaft, Schiffer, ...

Summary: similarities & differences

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

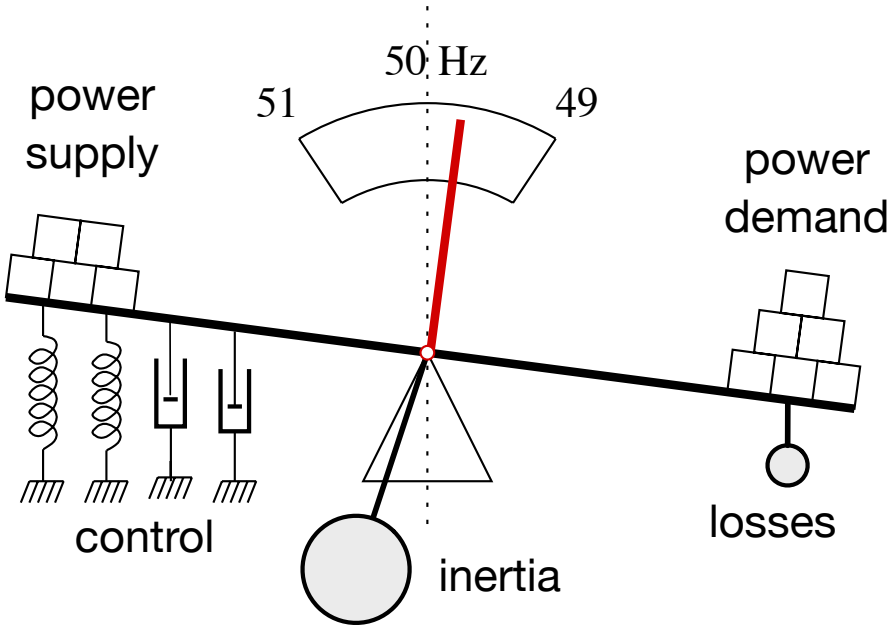


energy balances (neglecting small storage elements & losses):

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

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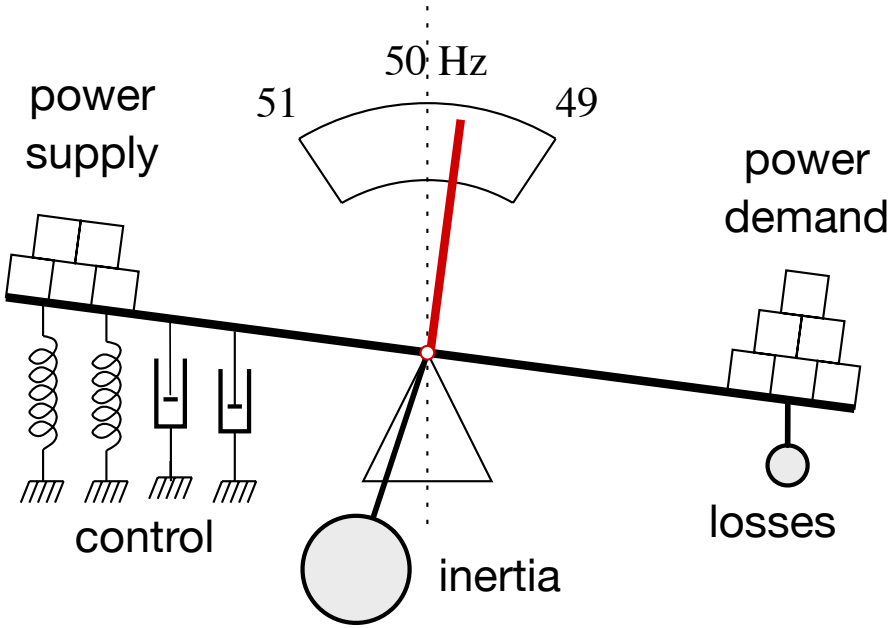
$$\tfrac{d}{dt}\ \tfrac{1}{2} v_{\text{dc}}^\top C_{\text{dc}} v_{\text{dc}} = i_{\text{dc}}^\top v_{\text{dc}} - \boldsymbol{i}_f^\top \boldsymbol{v}_g + 0$$

Antipodal control characteristics

- large M vs. negligible C_{dc} **energy storage** for disturbance rejection
- slow τ_m vs. fast i_{dc} **actuation of the energy supply** (though i_{dc} constrained)
- limited vs. full **actuation of the energy conversion** via L_θ & modulation $\boldsymbol{m}$

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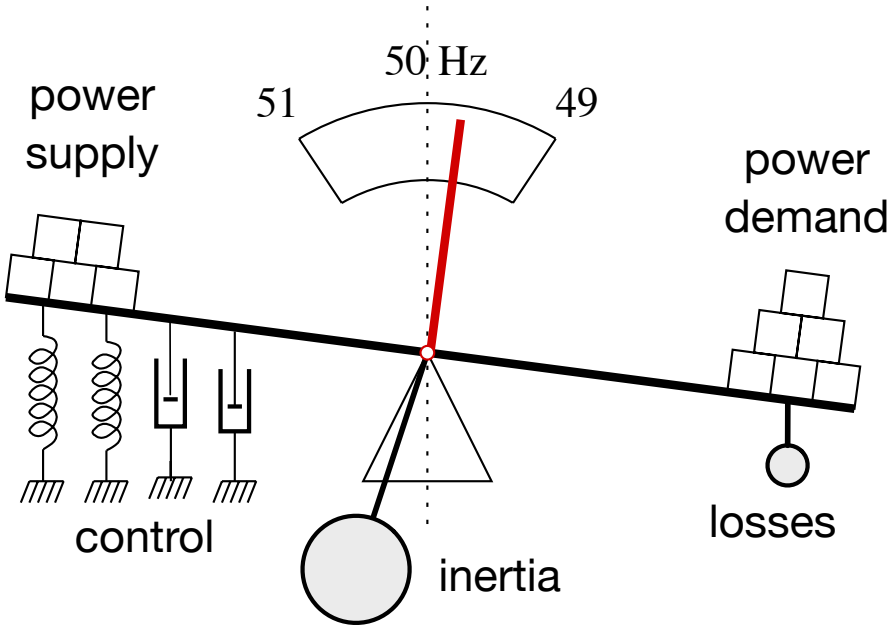
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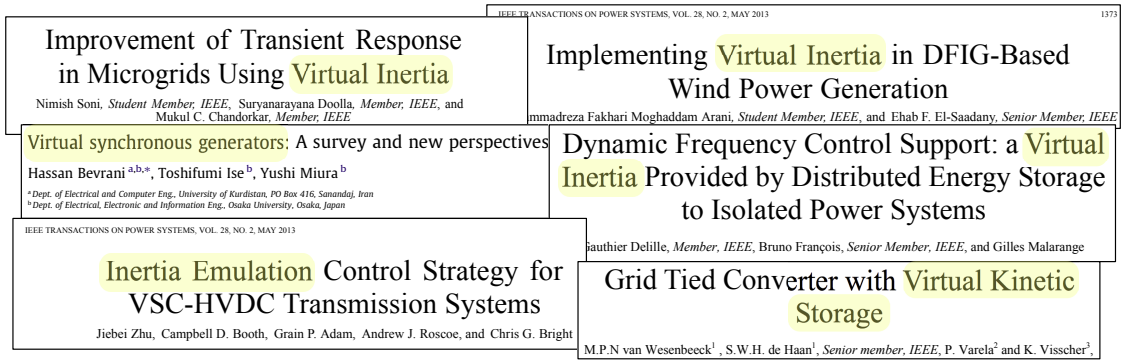
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robust vs. agile
resilient vs. fragile
slow vs. fast actuation
physical vs. control system

Preview: pitfalls of naive inertia emulation

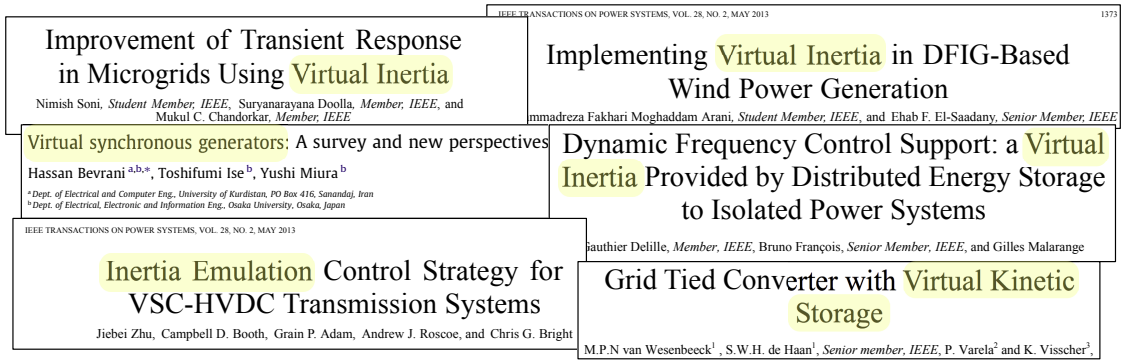
(naive) **baseline solution** :
inverter + storage + control
$\rightarrow$ emulate **virtual inertia**



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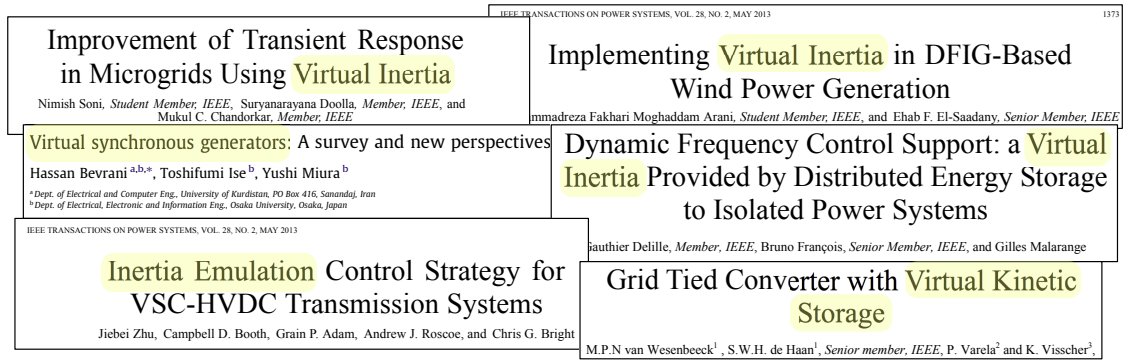
. . . can & has been done **but**
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Improvement of Transient Response in Microgrids Using Virtual Inertia

Nimish Soni, *Student Member, IEEE*, Suryanarayana Doolla, *Member, IEEE*, and Mukul C. Chandorkar, *Member, IEEE*

IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 28, NO. 2, MAY 2013 1373

Implementing Virtual Inertia in DFIG-Based Wind Power Generation

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

Virtual synchronous generators: A survey and new perspectives

Hassan Bevrani [a,b,*], Toshifumi Ise [b], Yushi Miura [b]

[a] Dept. of Electrical and Computer Eng., University of Kurdistan, PO Box 416, Sanandaj, Iran
[b] Dept. of Electrical, Electronic and Information Eng., Osaka University, Osaka, Japan

Dynamic Frequency Control Support: a Virtual Inertia Provided by Distributed Energy Storage to Isolated Power Systems

authier Delille, *Member, IEEE*, Bruno François, *Senior Member, IEEE*, and Gilles Malarange

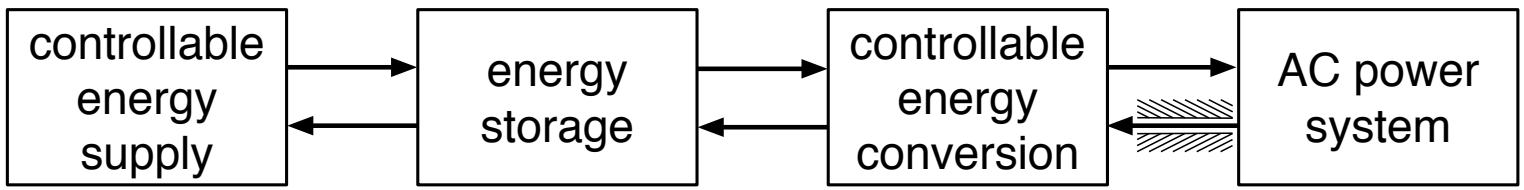
IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 28, NO. 2, MAY 2013

Inertia Emulation Control Strategy for VSC-HVDC Transmission Systems

Jiebei Zhu, Campbell D. Booth, Grain P. Adam, Andrew J. Roscoe, and Chris G. Bright

Grid Tied Converter with Virtual Kinetic Storage

M.P.N van Wesenbeeck[1], S.W.H. de Haan[1], *Senior member, IEEE*, P. Varela[2] and K. Visscher[3],

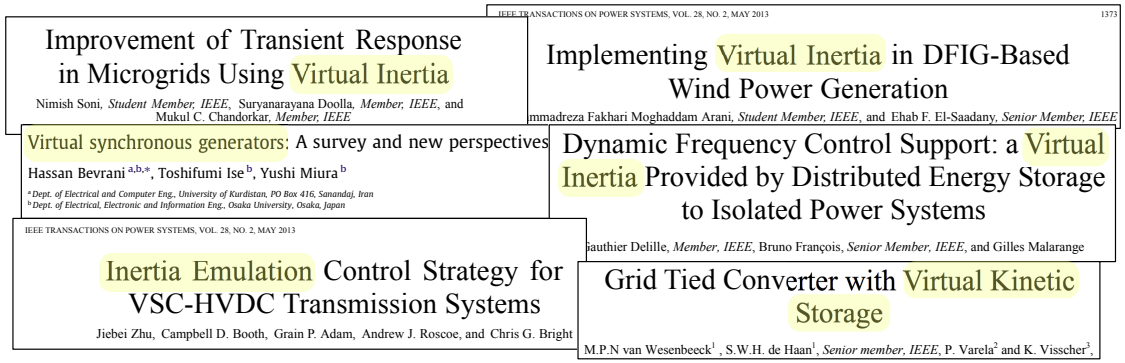


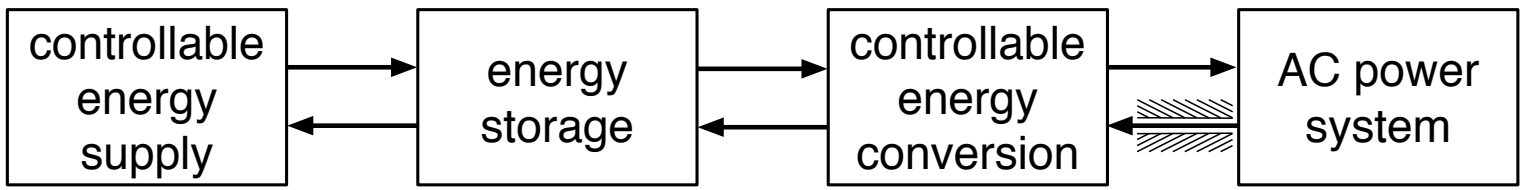
slow vs. fast large vs. small physics vs. control resilient vs. fragile

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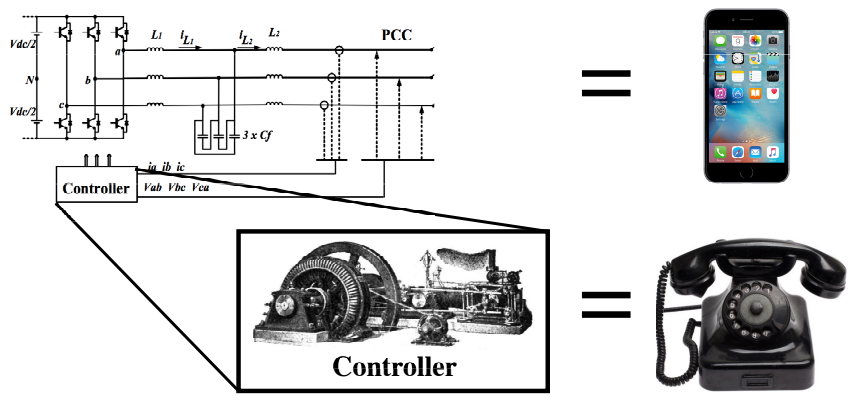
. . . can & has been done **but**
recall **antipodal characteristics**





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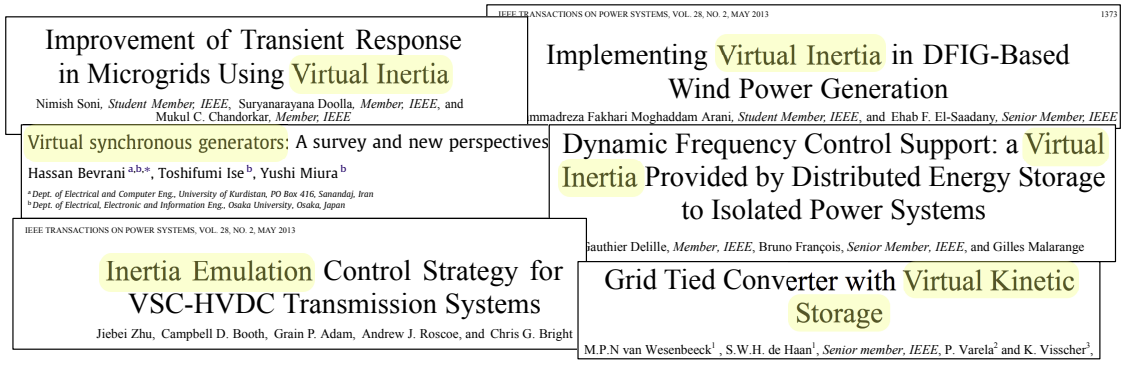
telecom analogy (E. Mallada)

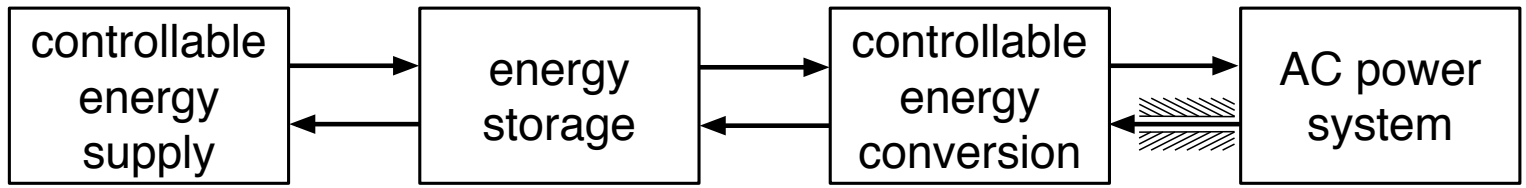


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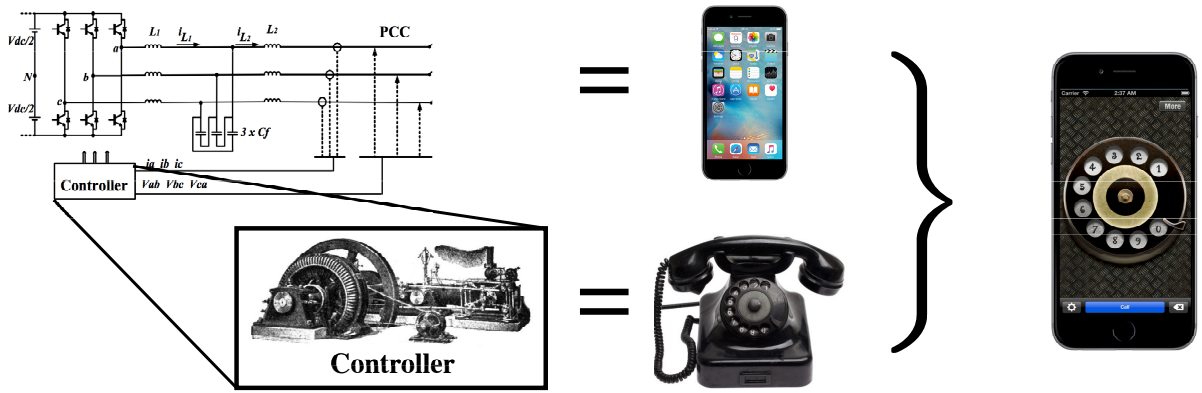
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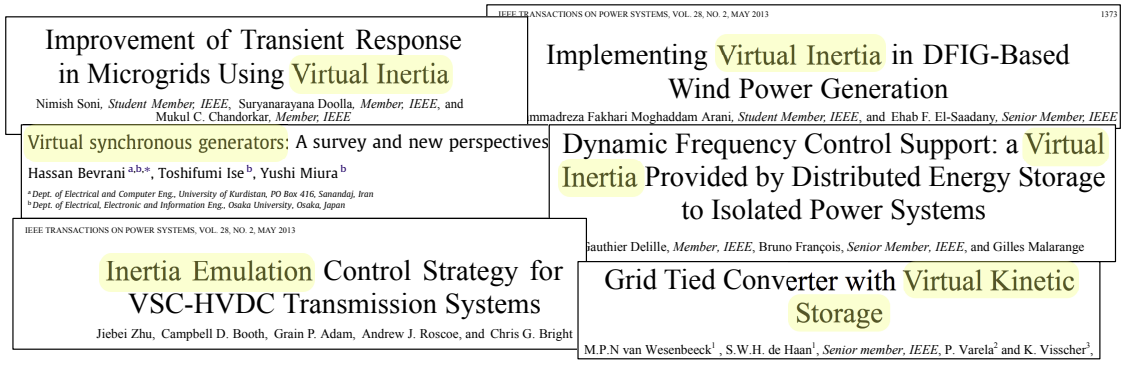
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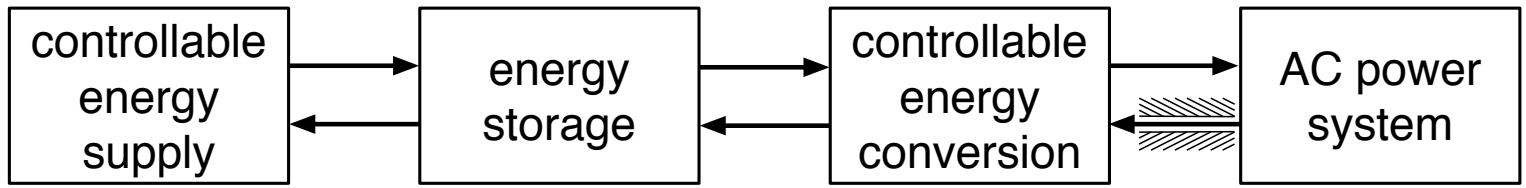


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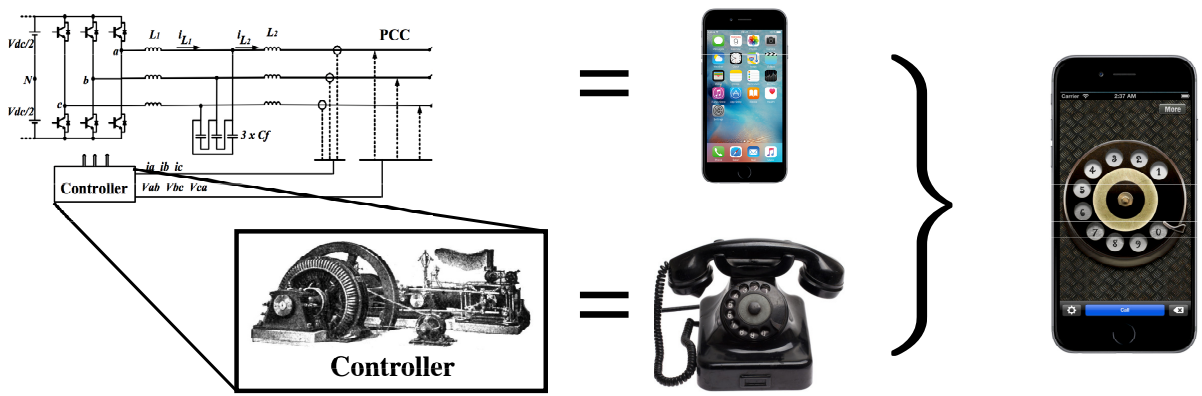




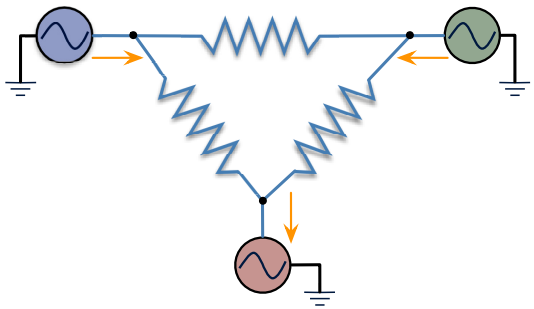
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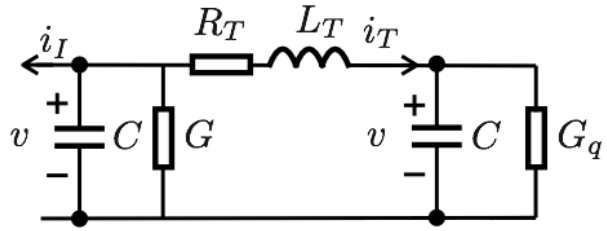
- works (under business-as-usual operation)
- there are better solutions (espec. for contingencies)



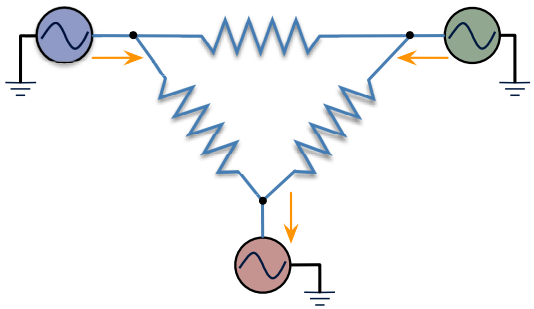
Modeling review: the network



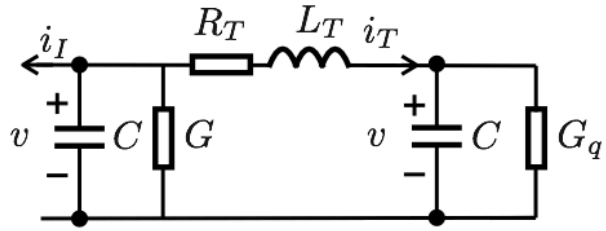
interconnecting lines via Π-models & **ODEs**



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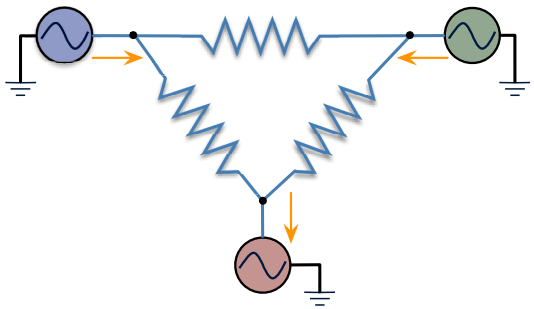
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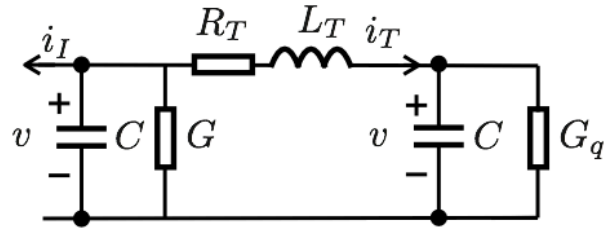
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$$\underbrace{\begin{bmatrix} i_1 \\ \vdots \\ i_n \end{bmatrix}}_{\text{nodal injections}} = \underbrace{\begin{bmatrix} \vdots & \ddots & \vdots & \iddots & \vdots \\ -y_{k1} & \cdots & \sum_{j=1}^{n} y_{kj} & \cdots & -y_{kn} \\ \vdots & \iddots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

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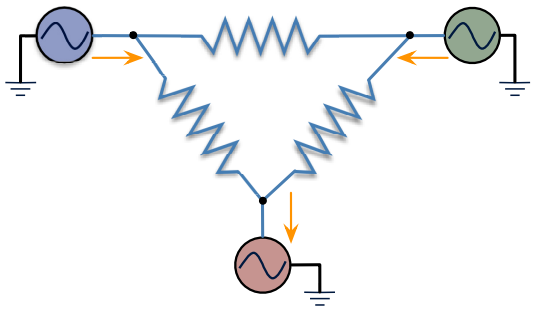
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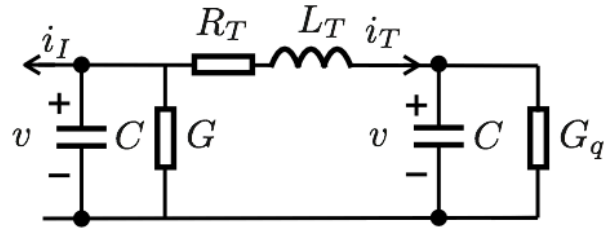
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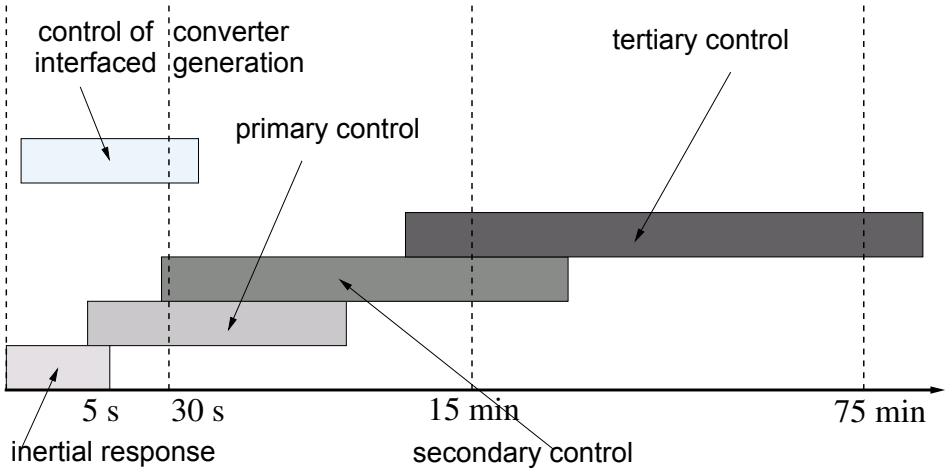
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- but quasi-steady-state **assumption is flawed** in low-inertia systems

Review: control specifications

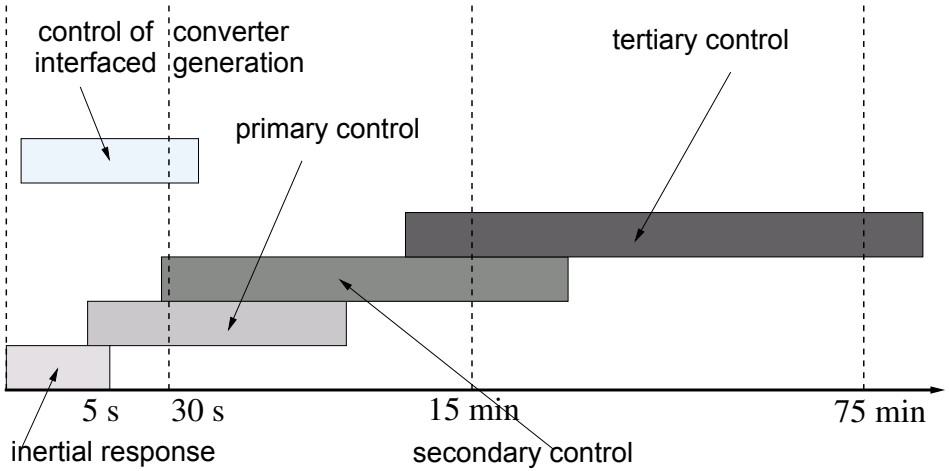
- **nominal synchronous operation**:
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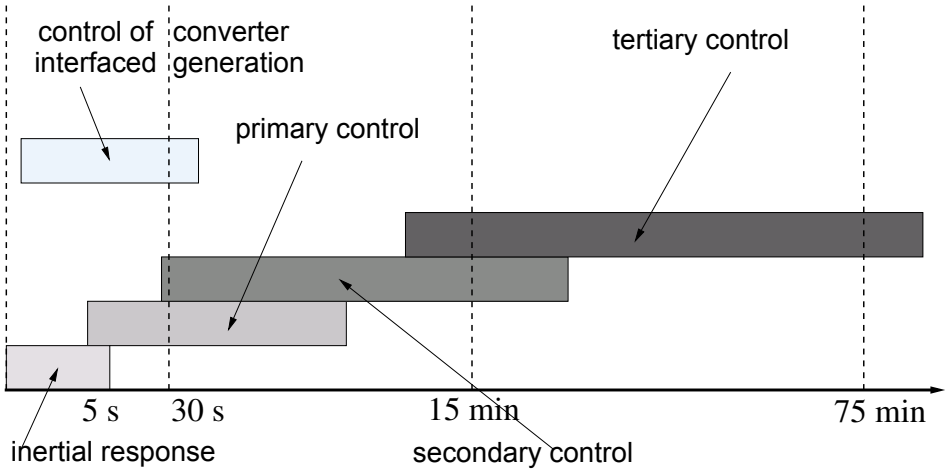
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Review: control specifications

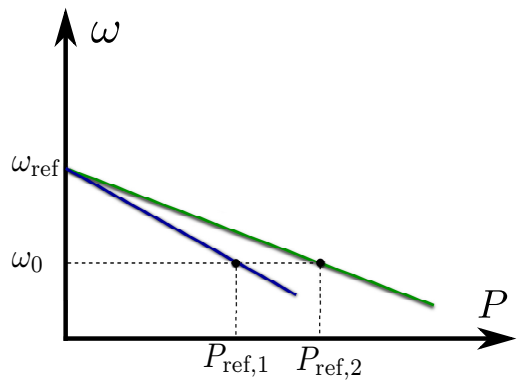


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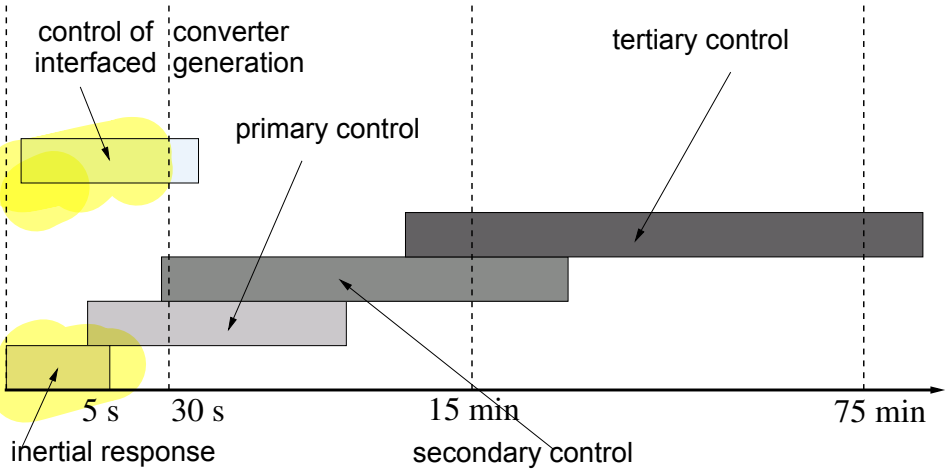
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$\rightarrow$ decentralized **droop/primary control** $P - P_{\text{ref}} \propto \omega - \omega_{\text{ref}}$



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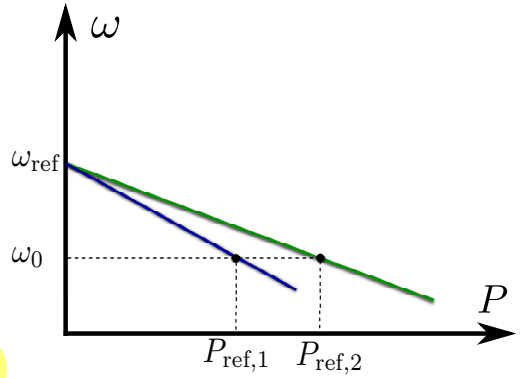


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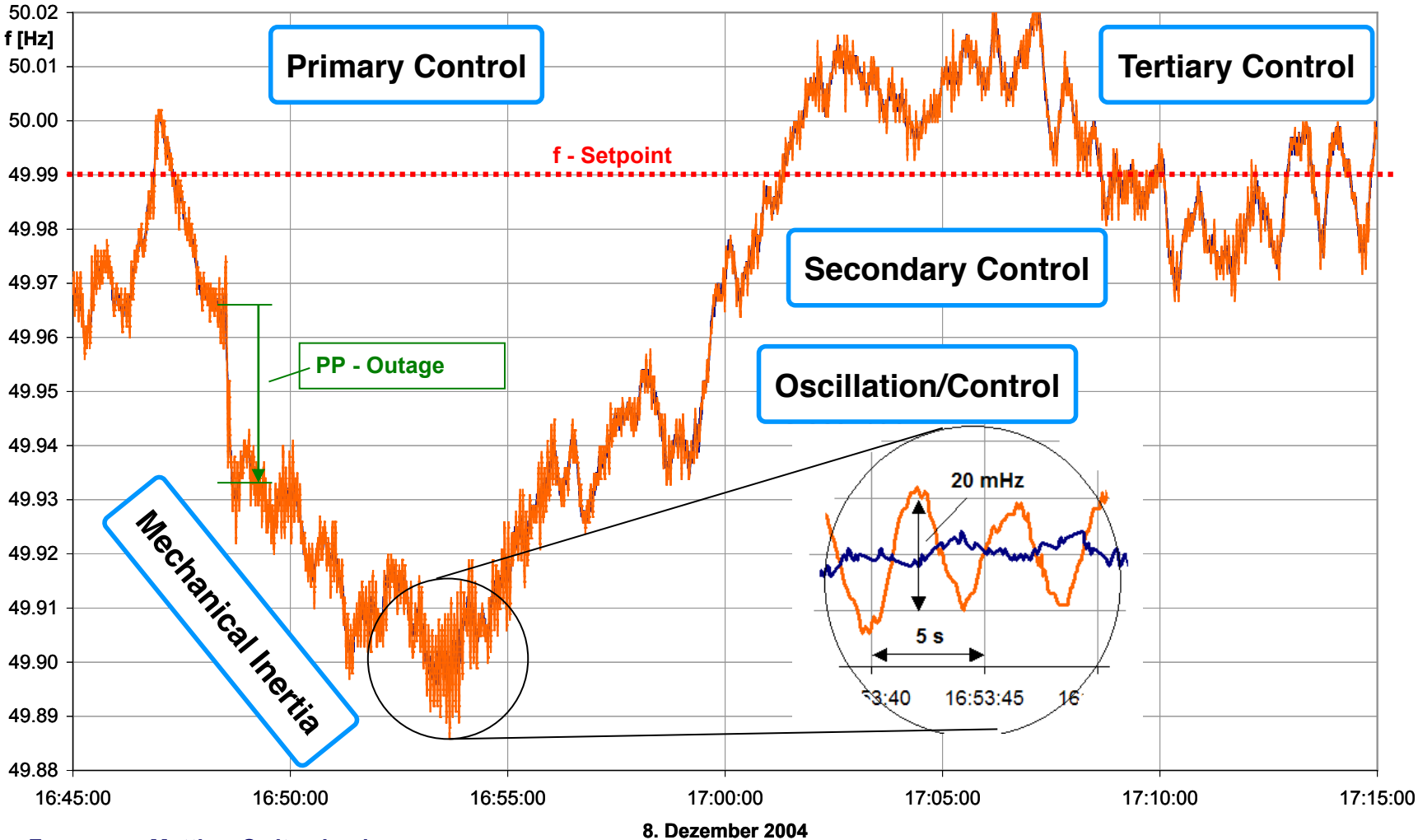
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- **secondary control:** regulation of $\omega \rightarrow \omega_{\text{ref}}$ (similar for $\boldsymbol{v}$)
- **tertiary control:** (re)scheduling of set-points

} similar as in conventional power systems

Review: controllers in action



Source: W. Sattinger, Swissgrid

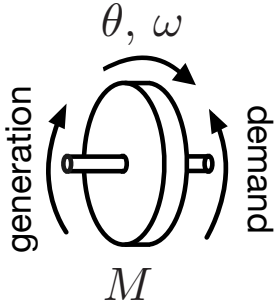
thought experiment:
extrapolation to
low-inertia systems

Insight: loss of inertia & frequency stability

We loose our giant electromechanical low-pass filter:

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

change of kinetic energy = instantaneous power balance

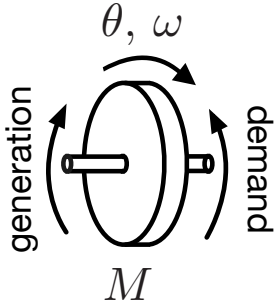


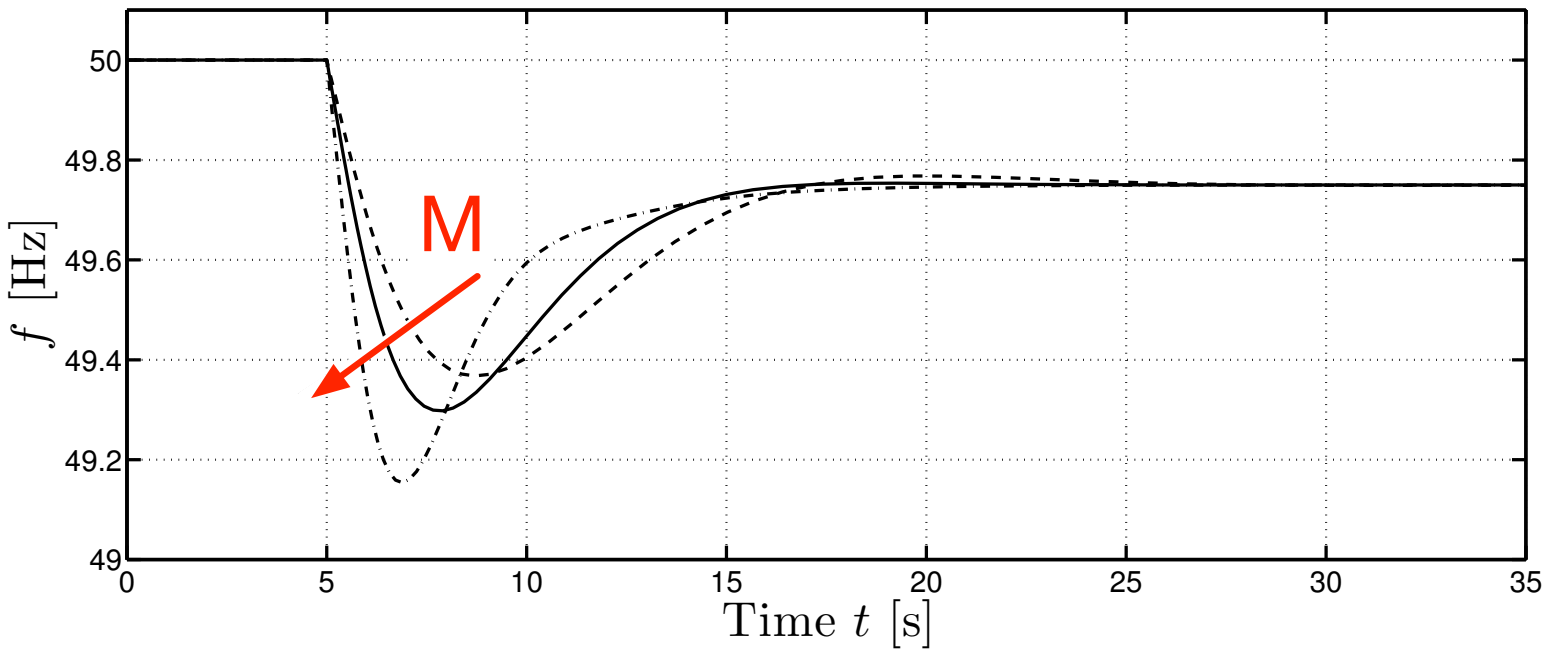
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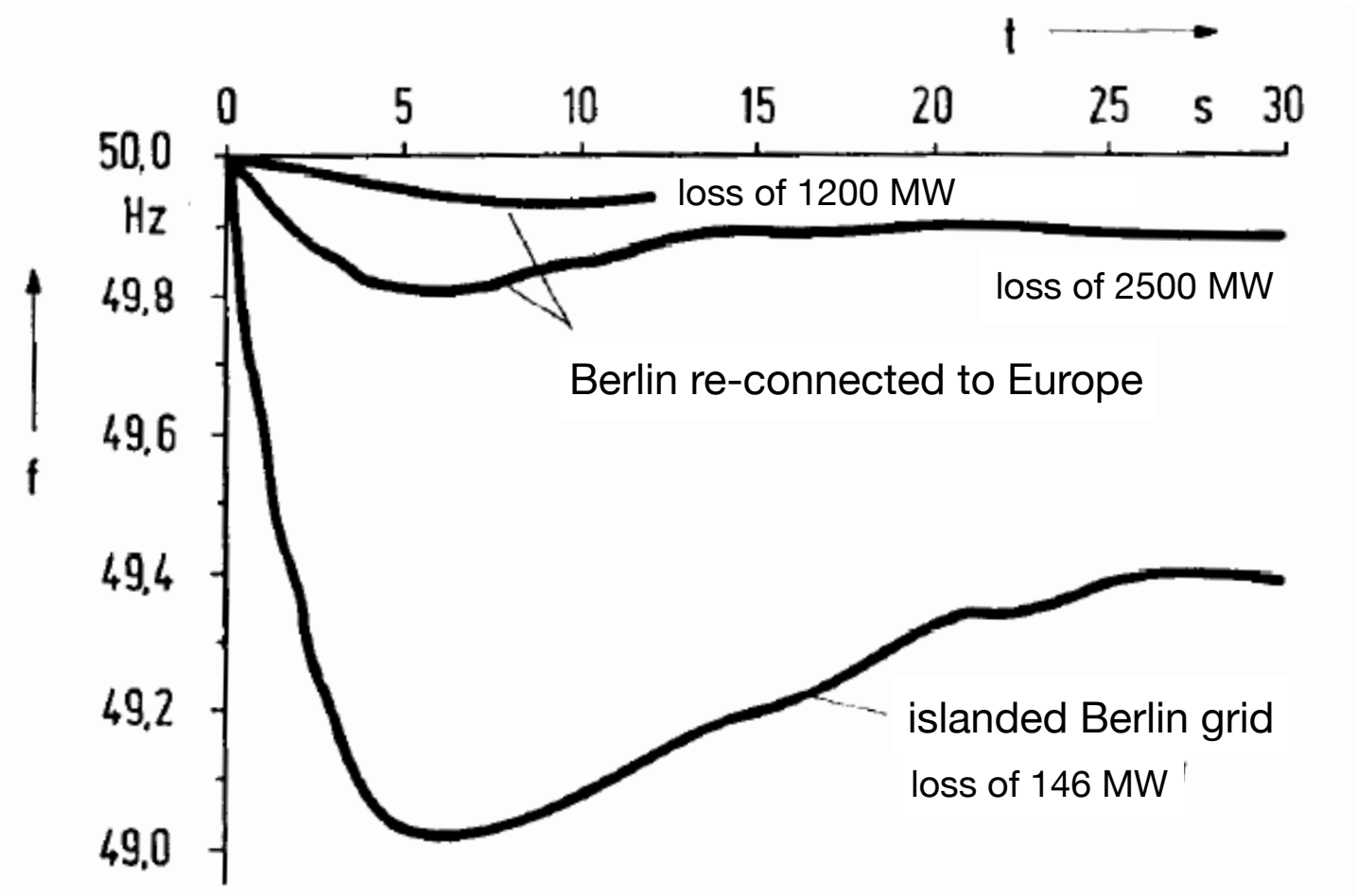
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Berlin post-fault curves: before and after



Source: *Energie-Museum Berlin*

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

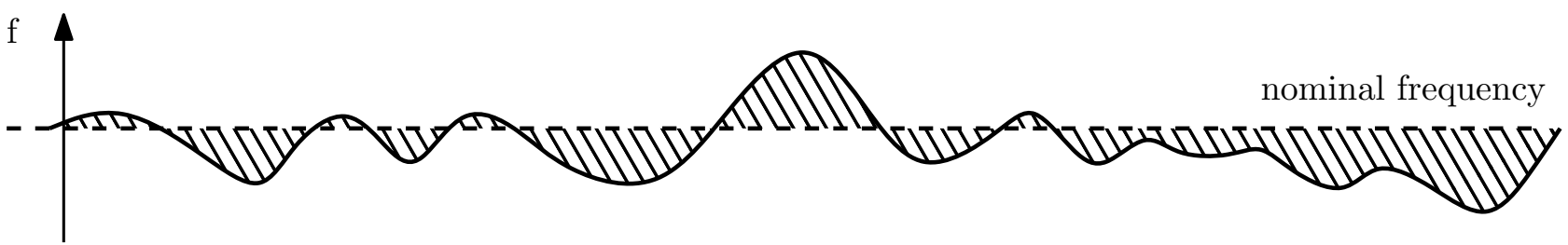
- the **physics** of a low-inertia system are not any longer dominated by the mechanical swing dynamics of synchronous machines
- not just loosing inertia but also tight **control** of frequency & voltage
- distributed generation will lead to different **contingencies** (more but smaller)
  exception: 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, . . .
- on the positive side: **actuation** is much faster!

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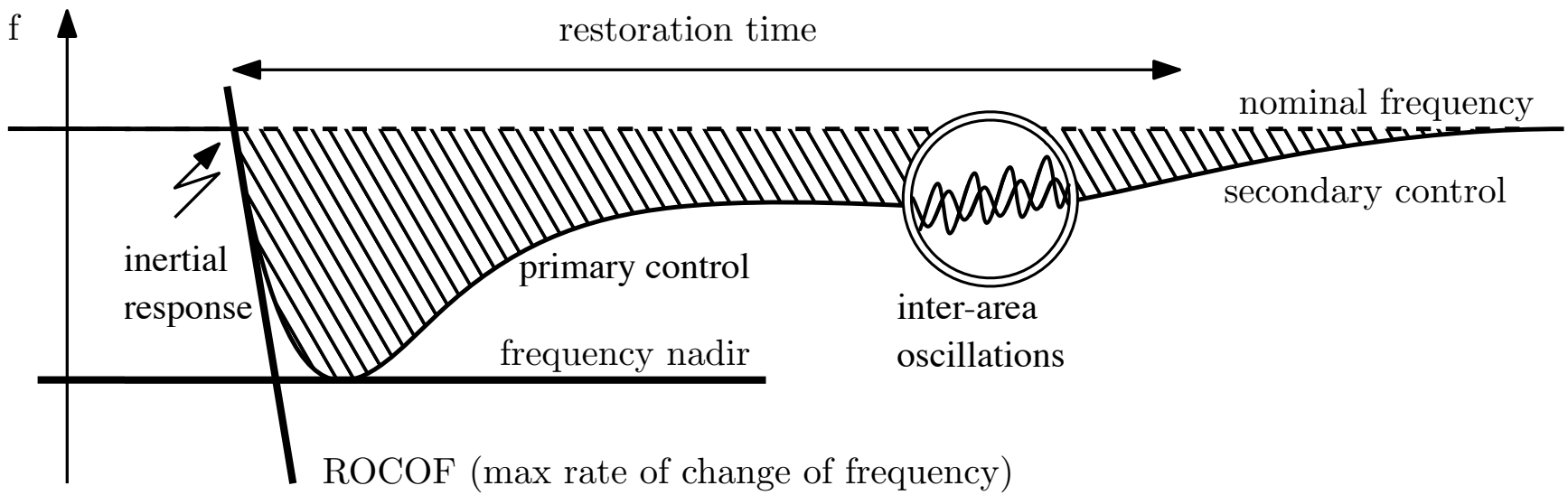
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$\rightarrow$ certainly more **brittle** behavior (faster time scales)

$\rightarrow$ for really low inertia levels **anything** can happen



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

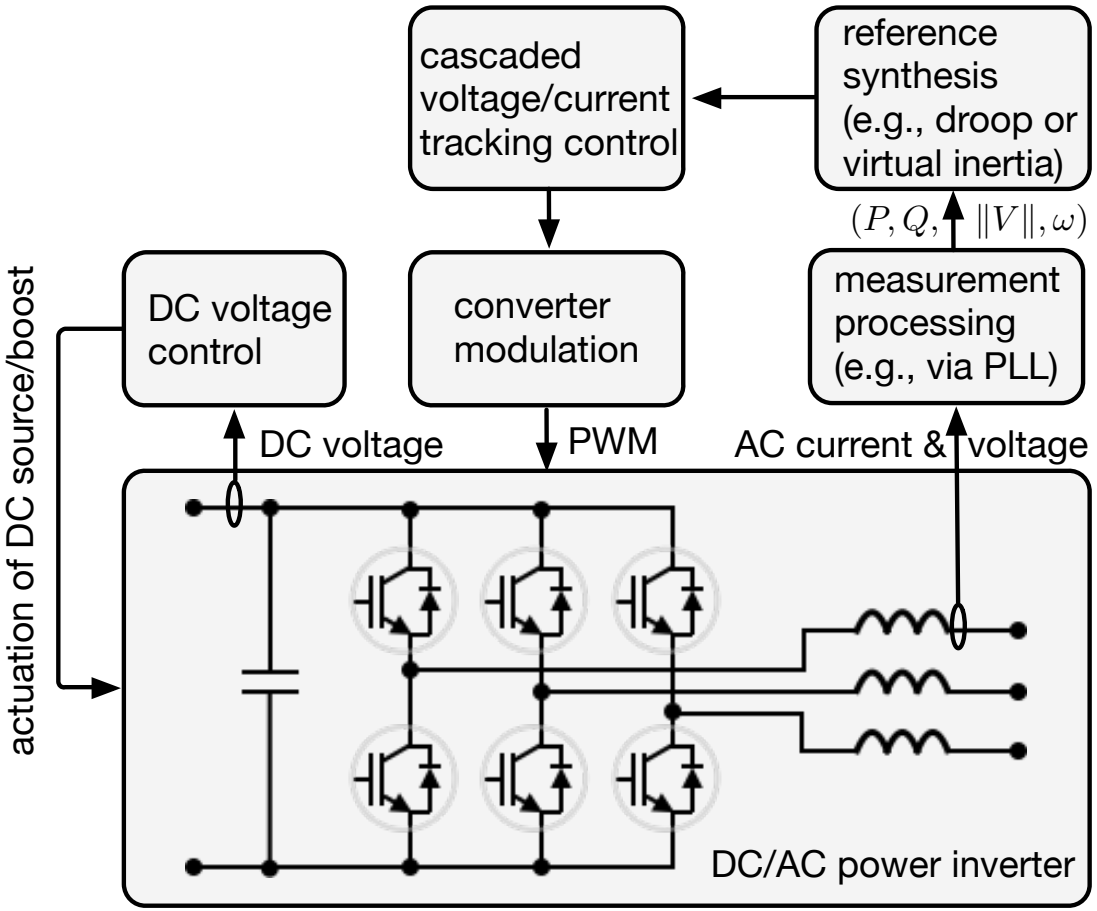


Outline

- Motivation: Challenges & Game Changers
- Power Converter Modeling & Control Specifications
- Elements of Power Electronics Control

decentralized control of power converters

Cartoon of power converter control

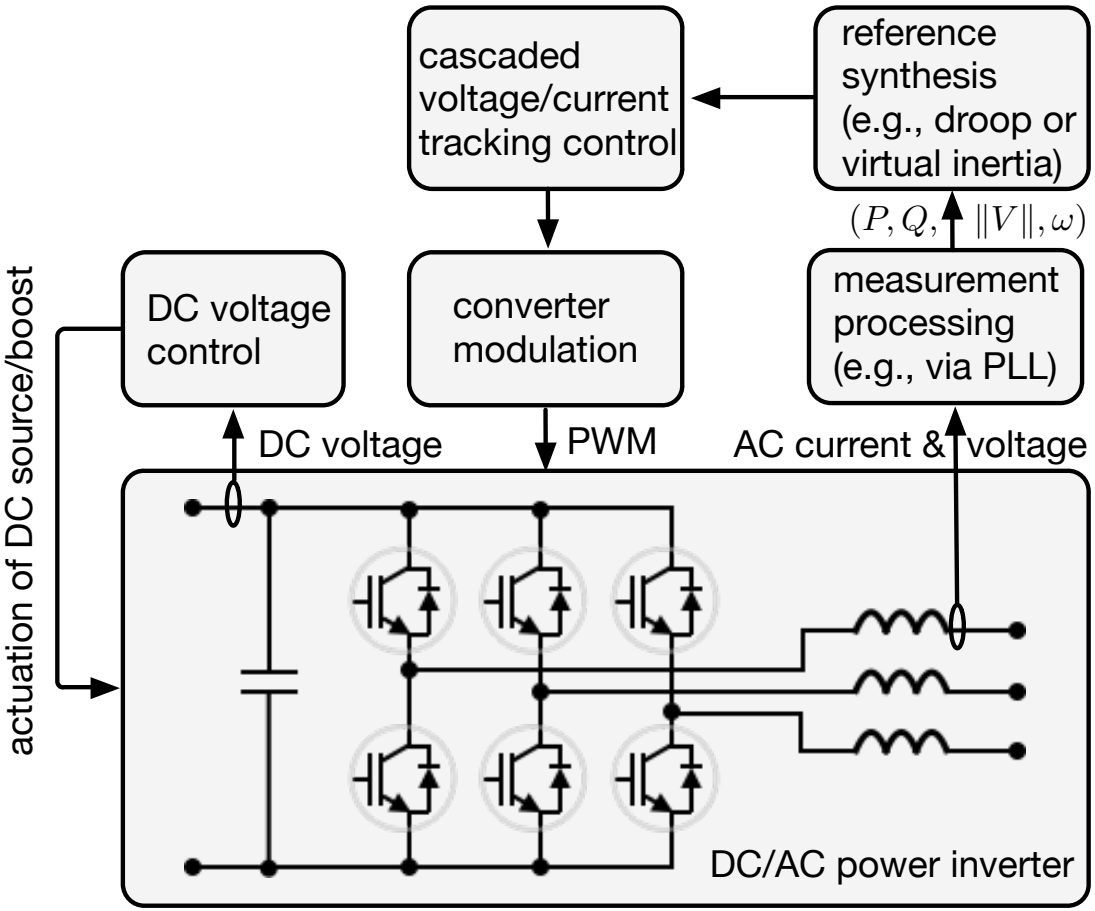


1. acquiring & processing of **AC measurements**
2. synthesis of **references** (voltage/current/power)

   "how would a synchronous generator respond now ?"
3. cascaded PI controllers to **track** references

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

Cartoon of power converter control



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3. cascaded PI controllers to **track** references

   assumption: no state constraints encountered
4. **actuation** via modulation
5. **energy balancing** via DC-side supply (P-control on DC voltage)

   assumption: unlimited power & instantaneous

Hierarchical power electronics architecture

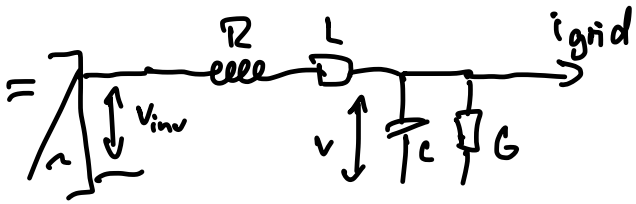
(covered on the board)

Converter - ac - equations (LC filter)

(in a rotating frame with frequency ω)

$$L\dot{i} = (-RI_2 + J\omega L)\, i + \underbrace{v_{inv}}_{m \cdot v_{dc}} - v$$

$$C\dot{v} = -(GI_2 + C\omega J)\cdot v + i - i_{grid}$$



Control objective: v should track a reference v_{ref} (e.g. "behave like a sync. machine")

- problem: v is not actuated, we can control only v_{inv}
- theory solution: $v_{inv} \rightarrow [G(s)] \rightarrow v$ — why not "invert the dynamics" as $v_{inv} = G^{-1}(s) \cdot v_{ref}$
- issue in practice: parametric uncertainty ⇝ model-based inversion performs poorly
- cascaded PI control is more robust!

- voltage loop to calculate an ideal current reference so that $v \approx v_{ref}$

$$L\dot{i} = (-RI_2 + J\omega L)\, i + \underbrace{v_{inv}}_{M \cdot v_{dc}} - v$$
$$C\dot{v} = -(GI_2 + C\omega J)\cdot v + i - i_{grid}$$

$$i_{ref} = \underbrace{i_{grid} + (GI_2 + C\omega J)\, v}_{\text{feedforward (cancellation)}} - \underbrace{k_p (v - v_{ref})}_{\text{stabilization}} - \underbrace{k_I \int_0^t v - v_{ref}\, d\tau}_{\text{regulation}}$$

- current loop so that $i \approx i_{ref}$

$$v_{inv} = \underbrace{v + (RI_2 + J\omega L)\, i}_{\text{feedforward}} - \underbrace{k_p' (i - i_{ref})}_{\sim} - \underbrace{k_I' \int_0^t i - i_{ref}\, d\tau}_{\sim}$$

- notes:
  - in practice often the feedforward is not implemented
  - enforce a roughly factor 10 time-scale separation between the loops / better: backstepping

Converter power balance:

- modulation is energy neutral (just conversion)
- power balance is controlled by i_{dc} and it is indicated by v_{dc}: $\frac{d}{dt}\frac{1}{2}v_{dc}^2 C_{dc} = \underbrace{i_{dc} \cdot v_{dc}}_{\text{dc supply}} - \underbrace{m i \cdot v_{dc}}_{\text{to the switches}}$
- DC-P control:

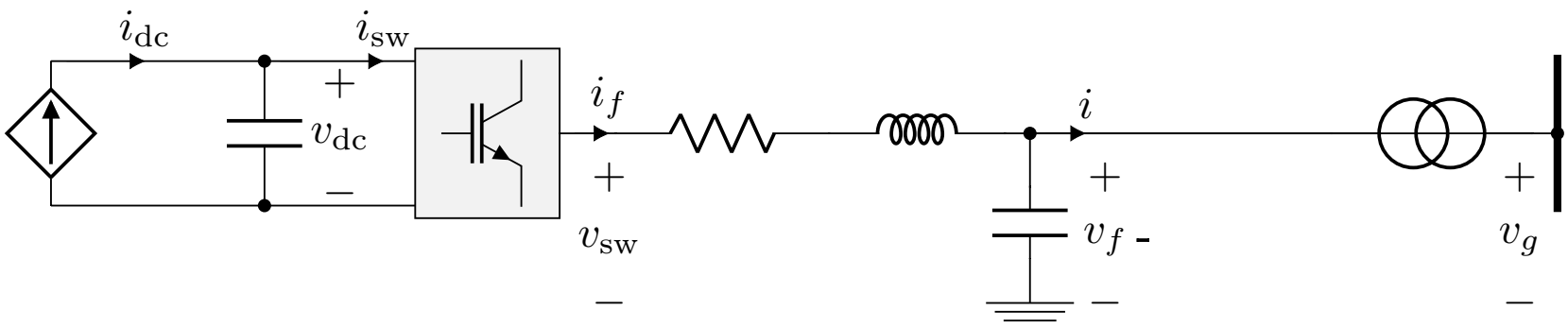
$$i_{dc} = i_{dc,ref} + k\,(v_{dc} - v_{dc,ref})$$

$i_{dc,ref}$: feedforward; k: high-gain P-control

(implicit assumption: dc source can deliver)

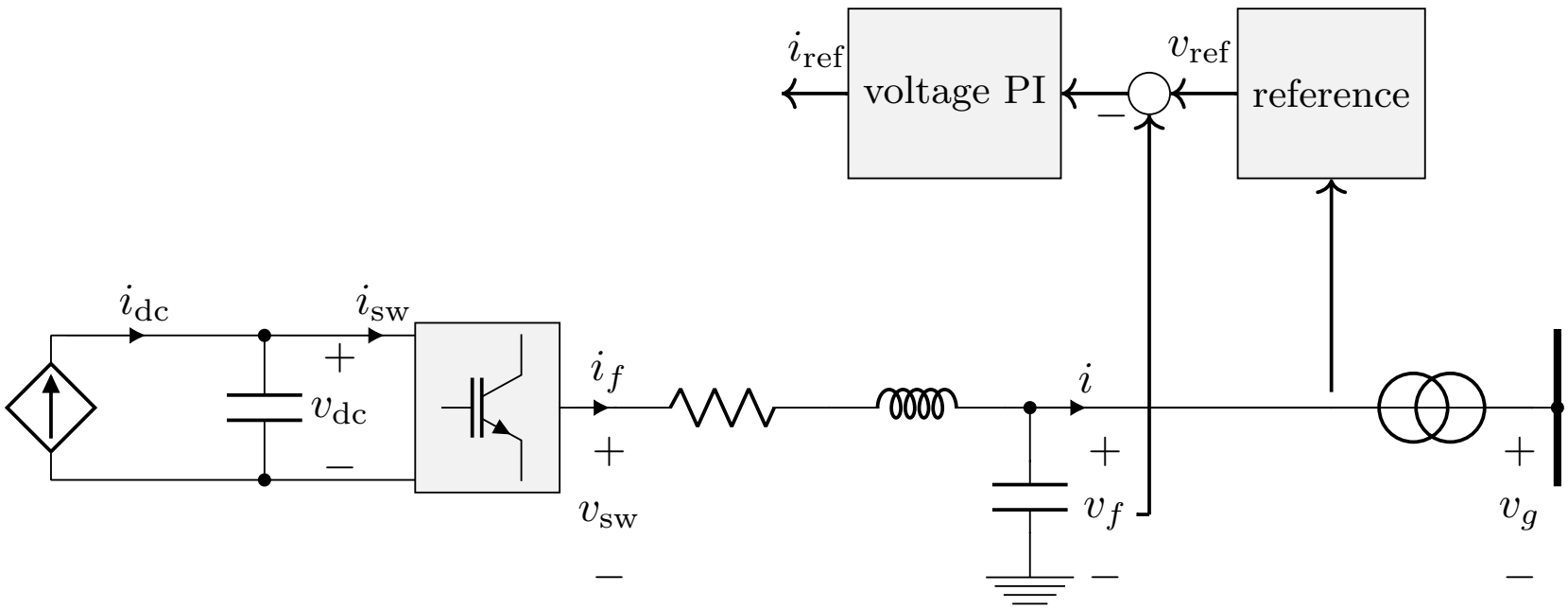
Example: Inner/Outer Control Loops

figure provided by Irina Subotić



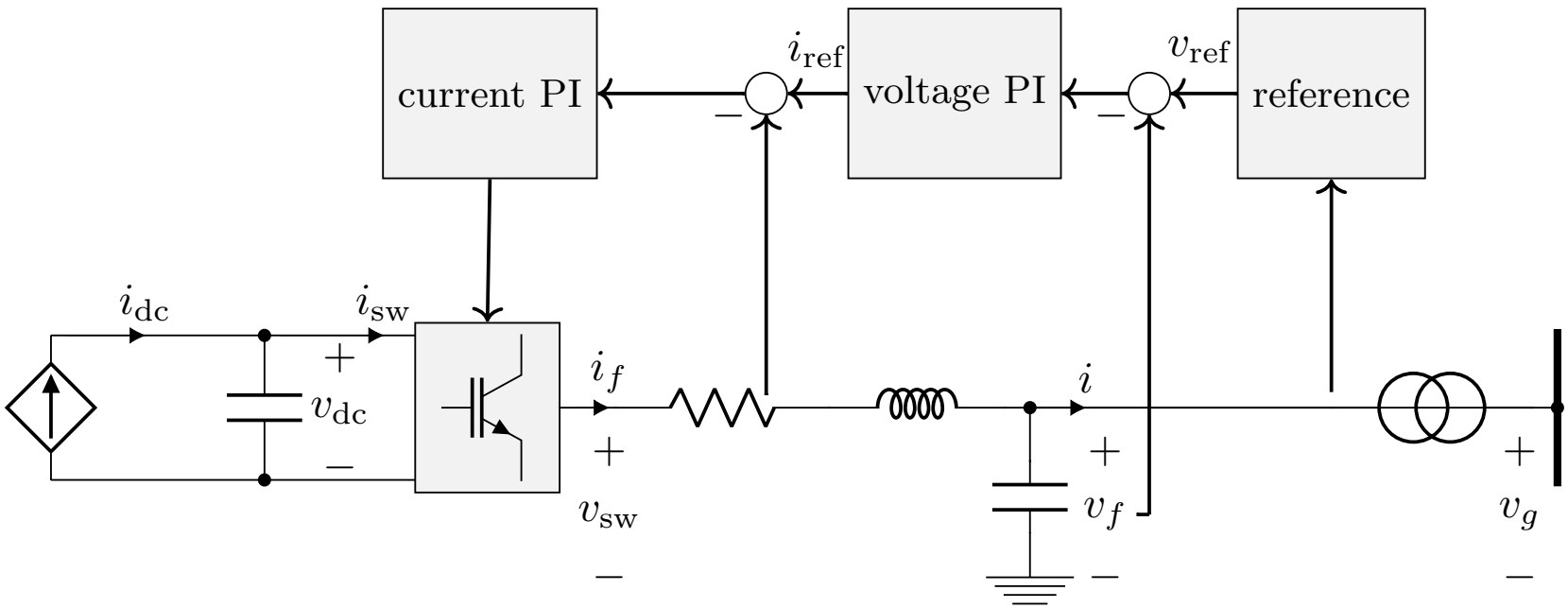
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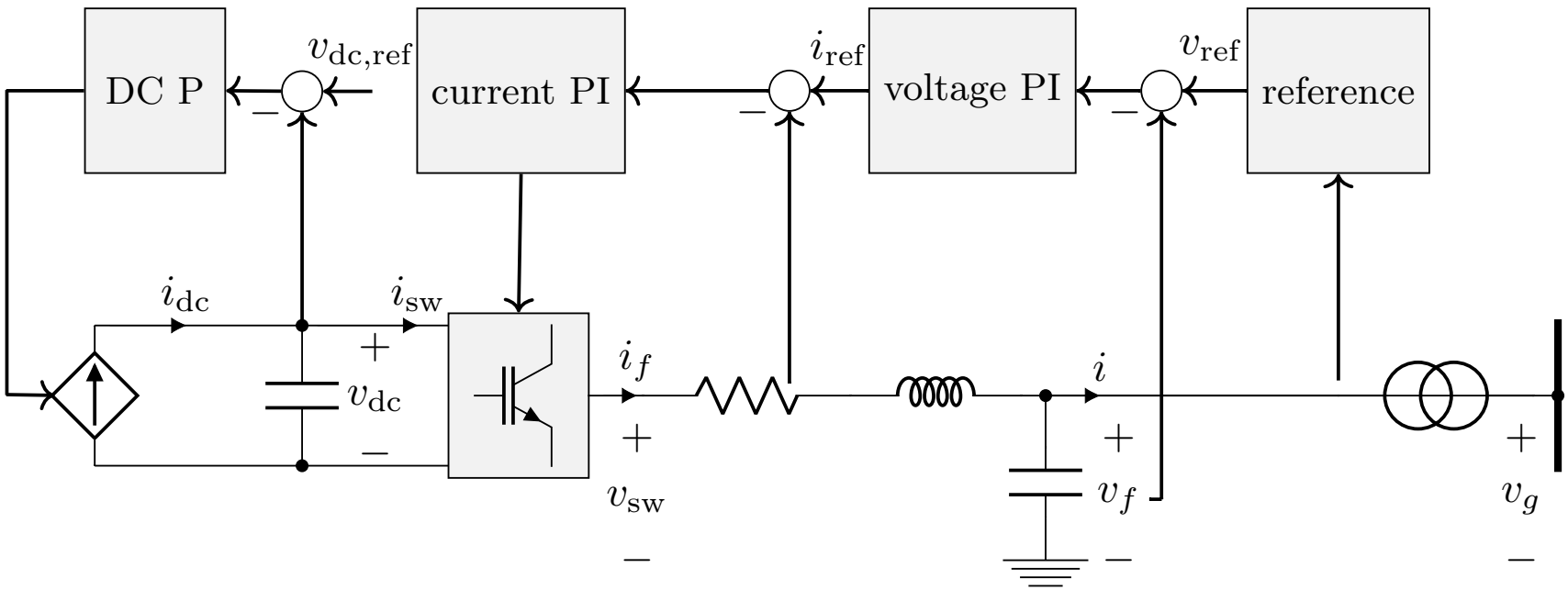
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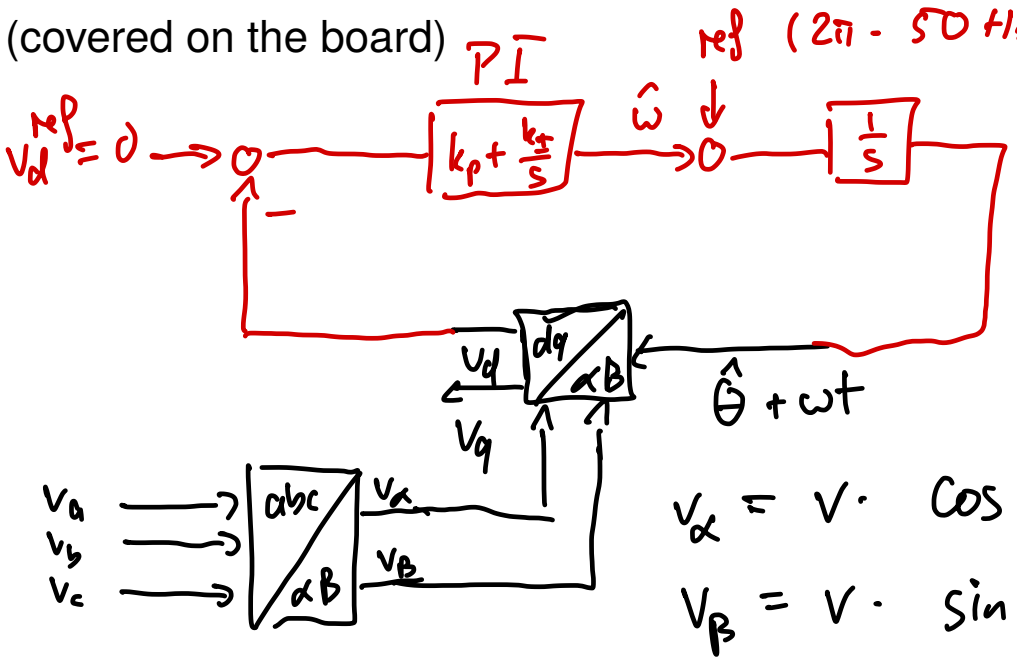
Example: Inner/Outer Control Loops

figure provided by Irina Subotić



Crash course: synchronous reference frame (SRF) Phase-locked loop (PLL)

(covered on the board)



$$V_\alpha = V \cdot \cos(\theta + \omega t)$$

$$V_\beta = V \cdot \sin(\theta + \omega t)$$

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = R(\hat{\theta} + \omega t) \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = V \begin{bmatrix} -\sin(\hat{\theta} - \theta) \\ \cos(\theta - \hat{\theta}) \end{bmatrix} \overset{\uparrow}{=} V \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

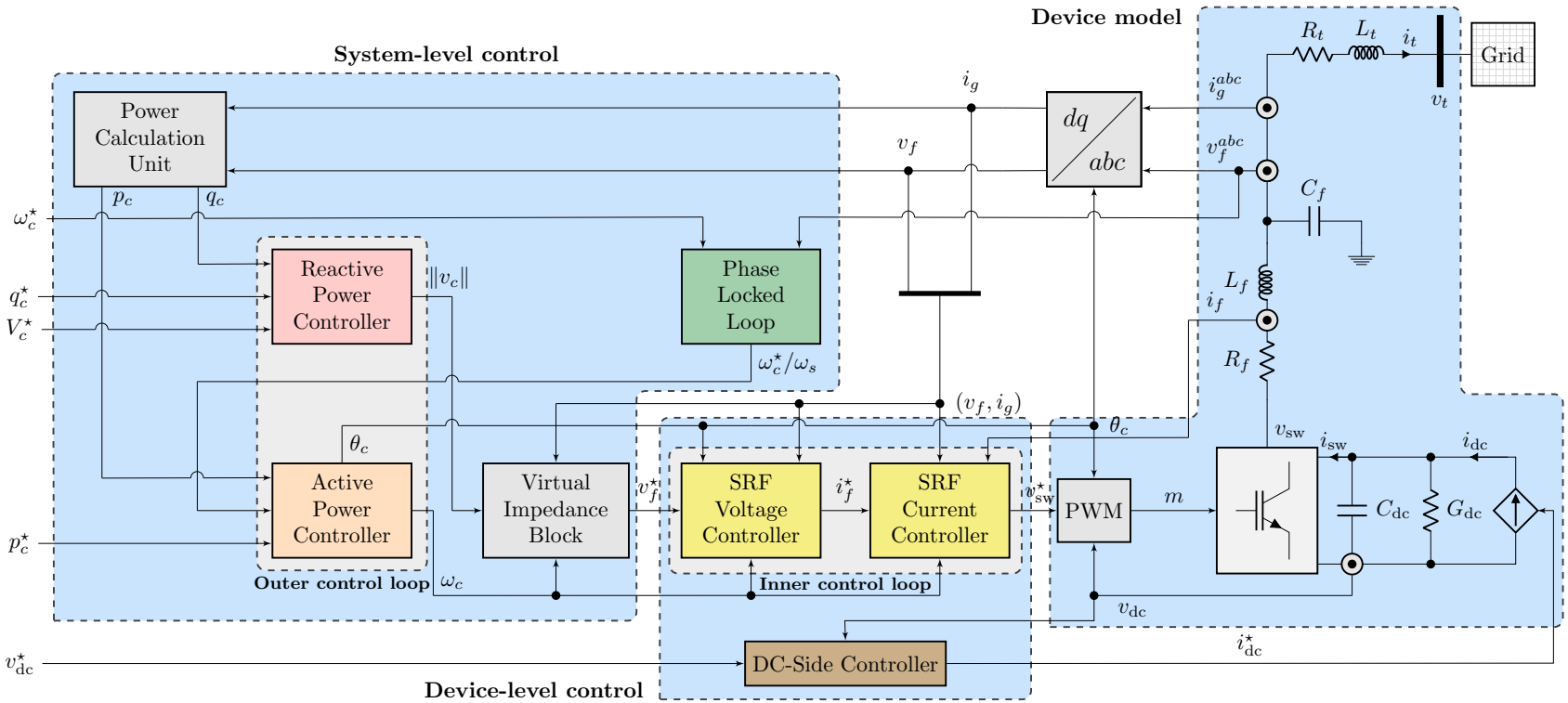
$\hat{\theta}$: estimate of θ

ideally $\hat{\theta} = \theta$

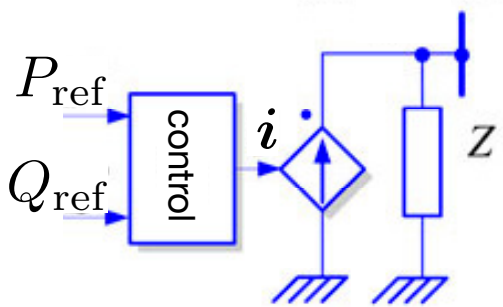
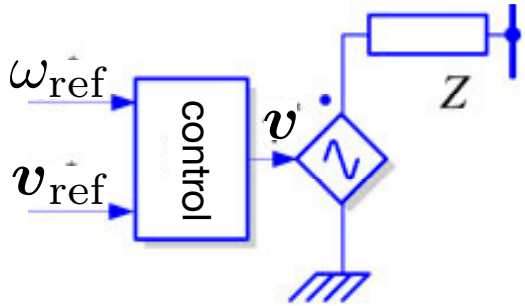
$\rightsquigarrow$ solve by PI control

Example: PLL - Based Control Architecture

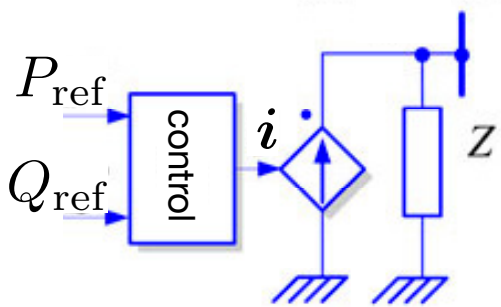
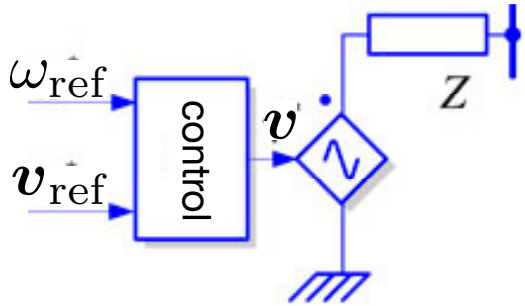
figure provided by Uroš Marković



Grid-forming & following converter control

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

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

Remark: definitions are debated

- put 20 experts in a room $\ldots \rightarrow$ no universal definition & many hybrid concepts

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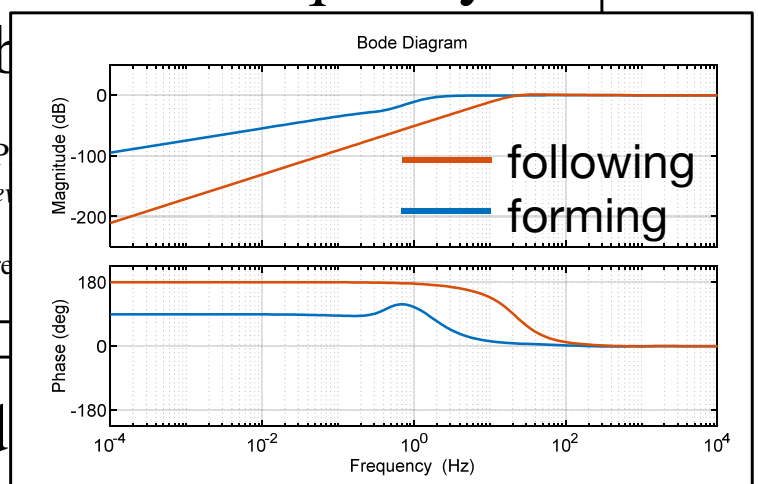
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Remark: definitions are debated

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

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

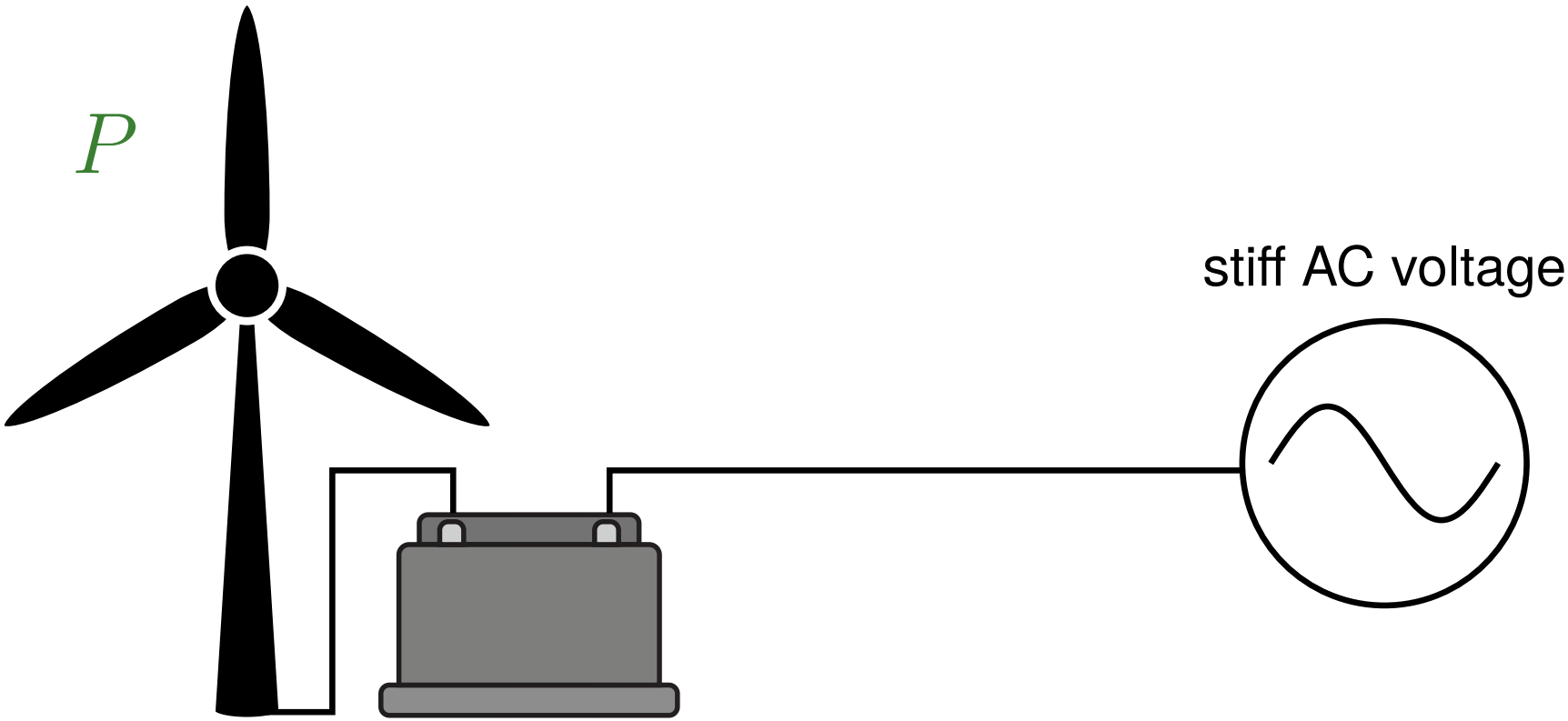
Debry Marie-Sophie, Denis Guillaume, P
Réseau de Transport d'Electricité (Research and Dev
La Défense
marie-sophie.debry / guillaume.denis / thibault.pre



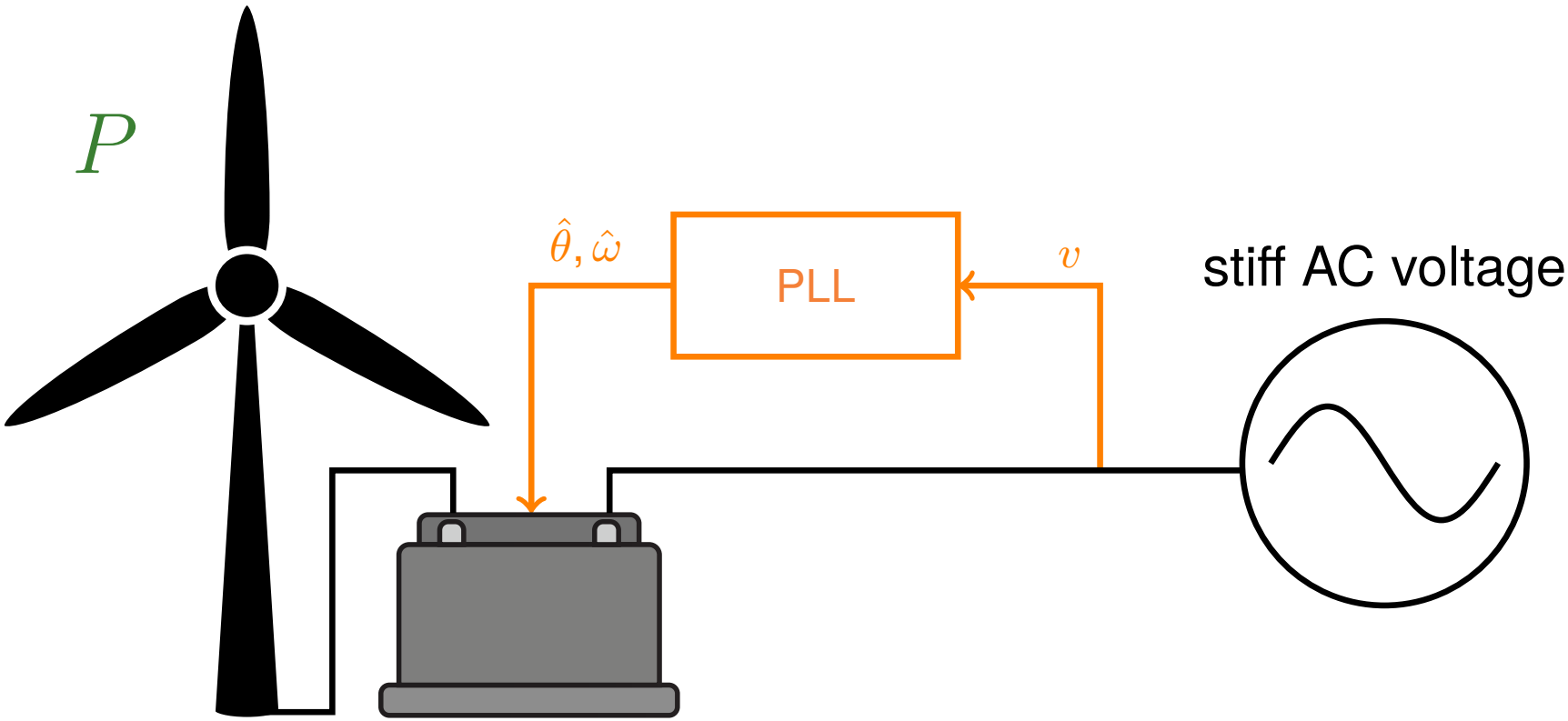
$\mathcal{H}_\infty$-Control of Grid-Connected
Objectives and Decentralized Stability Certificates

Linbin Huang, Huanhai Xin, and Florian Dörfler

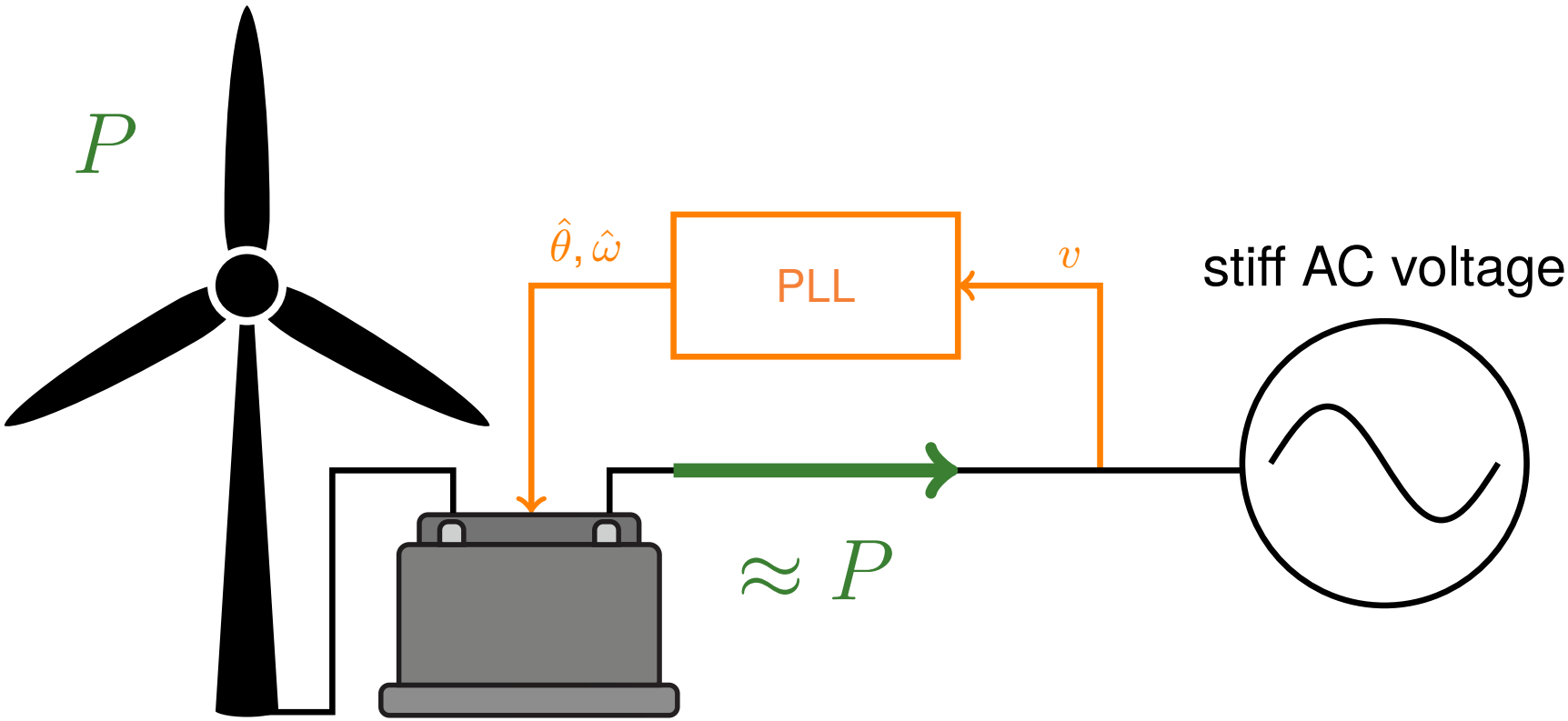
Limitations of grid-following control



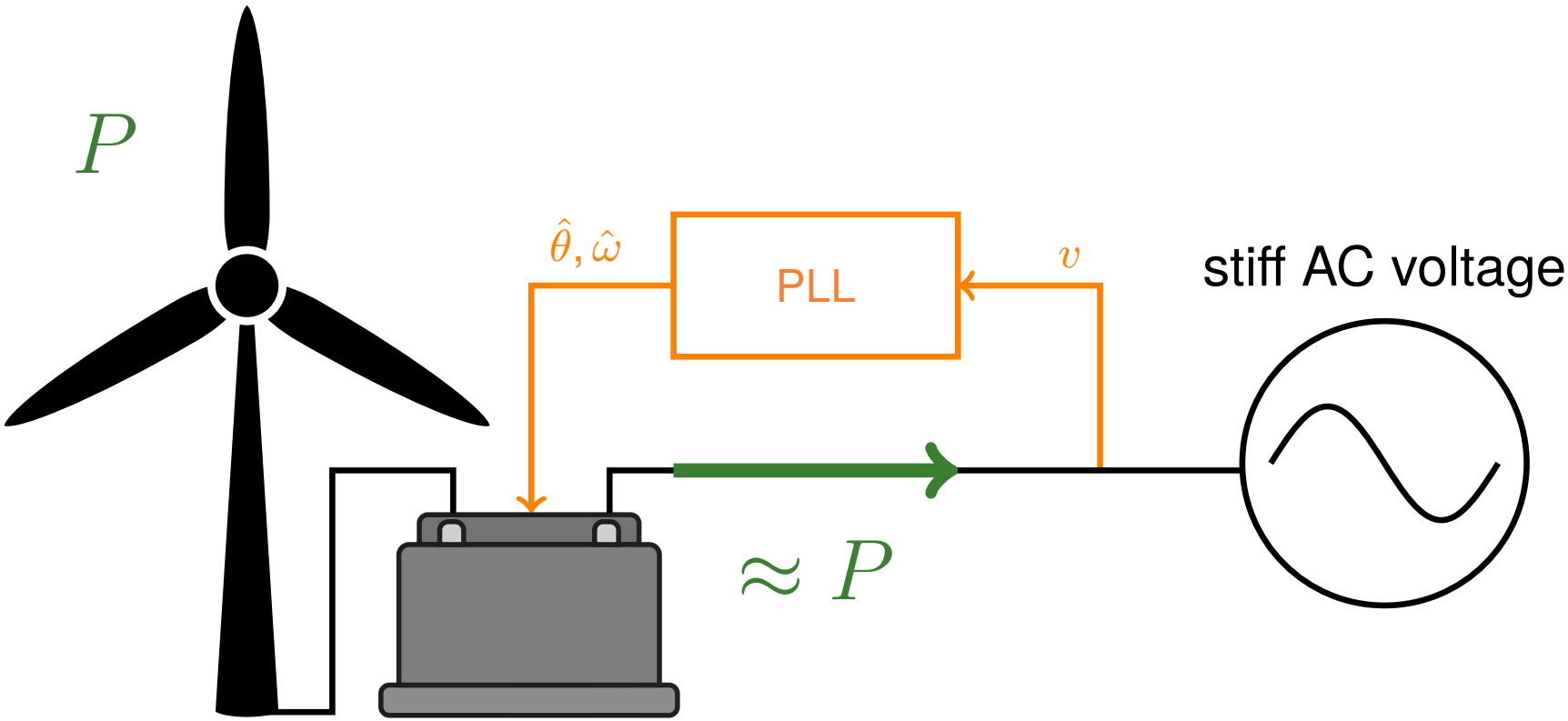
Limitations of grid-following control



Limitations of grid-following control



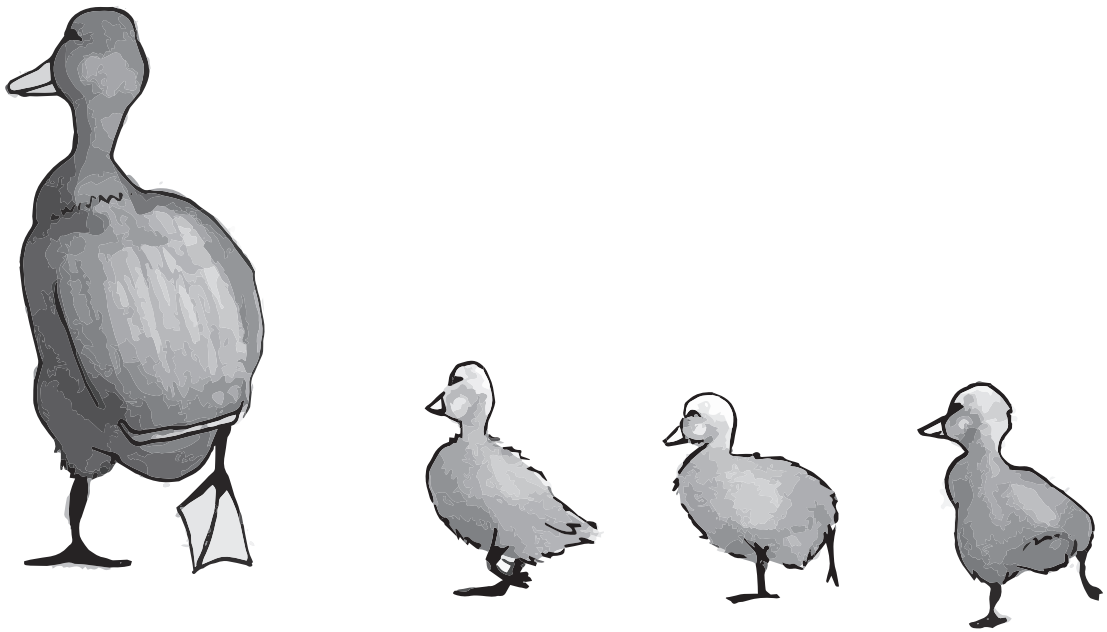
Limitations of grid-following control



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

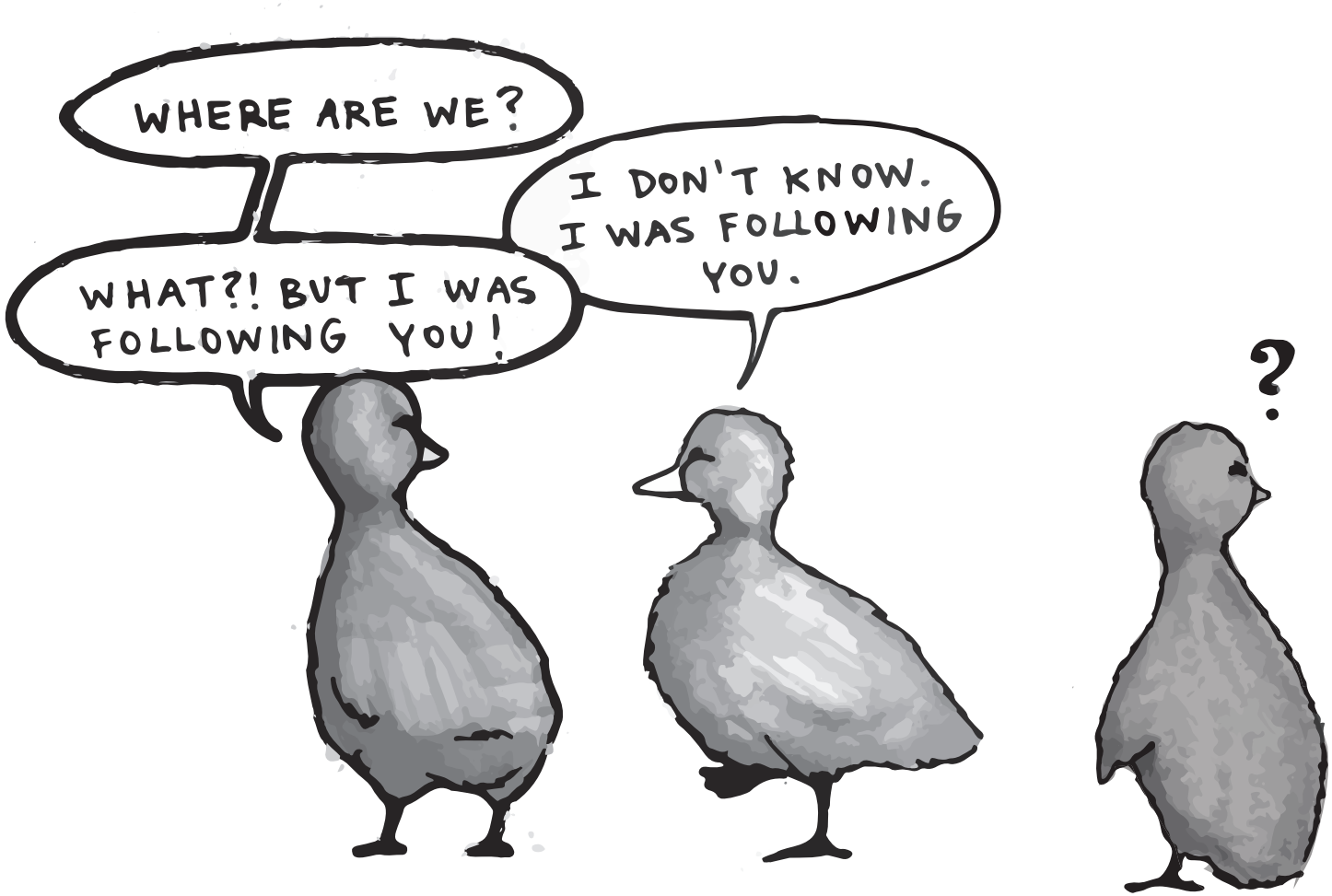
A stiff grid with grid-following sources . . .

figures by Outi Supponen



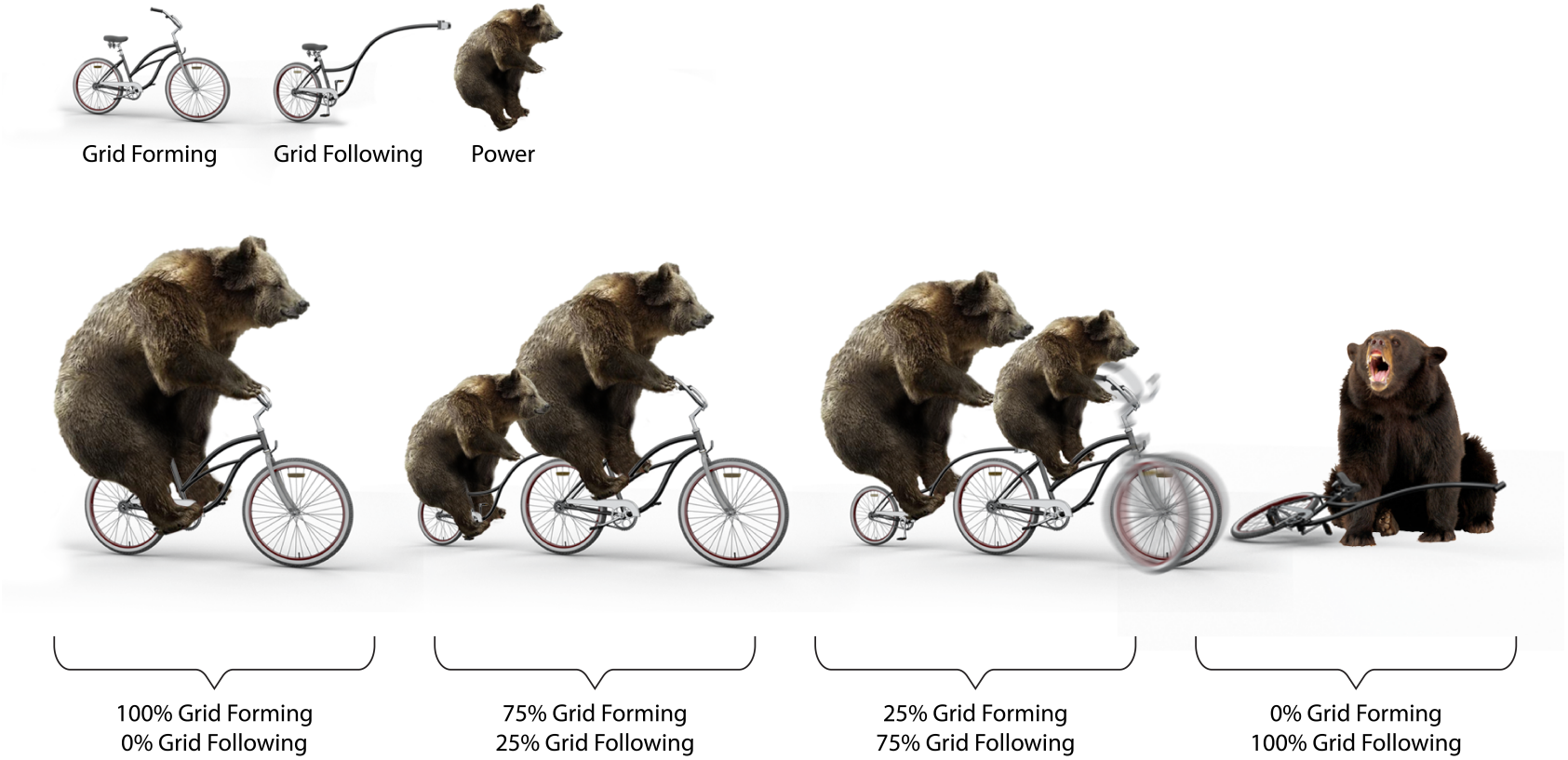
If everyone follows...

figures by Outi Supponen



Fact: need XXX % grid-forming converters

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



Naive baseline: virtual inertia emulation

IRELAND

Hybrid storage system looks to Ireland's services market

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

Pure-play battery or hybrid grid energy storage?

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Improvement of Transient Response in Microgrids Using Virtual Inertia

Nimish Soni, *Student Member, IEEE*, Suryanarayana Doolla, *Member, IEEE*, and Mukul C. Chandorkar, *Member, IEEE*

IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 28, NO. 2, MAY 2013 1373

Implementing Virtual Inertia in DFIG-Based Wind Power Generation

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

Virtual synchronous generators: A survey and new perspectives

Hassan Bevrani [a,b,*], Toshifumi Ise [b], Yushi Miura [b]

[a] *Dept. of Electrical and Computer Eng., University of Kurdistan, PO Box 416, Sanandaj, Iran*
[b] *Dept. of Electrical, Electronic and Information Eng., Osaka University, Osaka, Japan*

Dynamic Frequency Control Support: a Virtual Inertia Provided by Distributed Energy Storage to Isolated Power Systems

…Gauthier Delille, *Member, IEEE*, Bruno François, *Senior Member, IEEE*, and Gilles Malarange

IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 28, NO. 2, MAY 2013

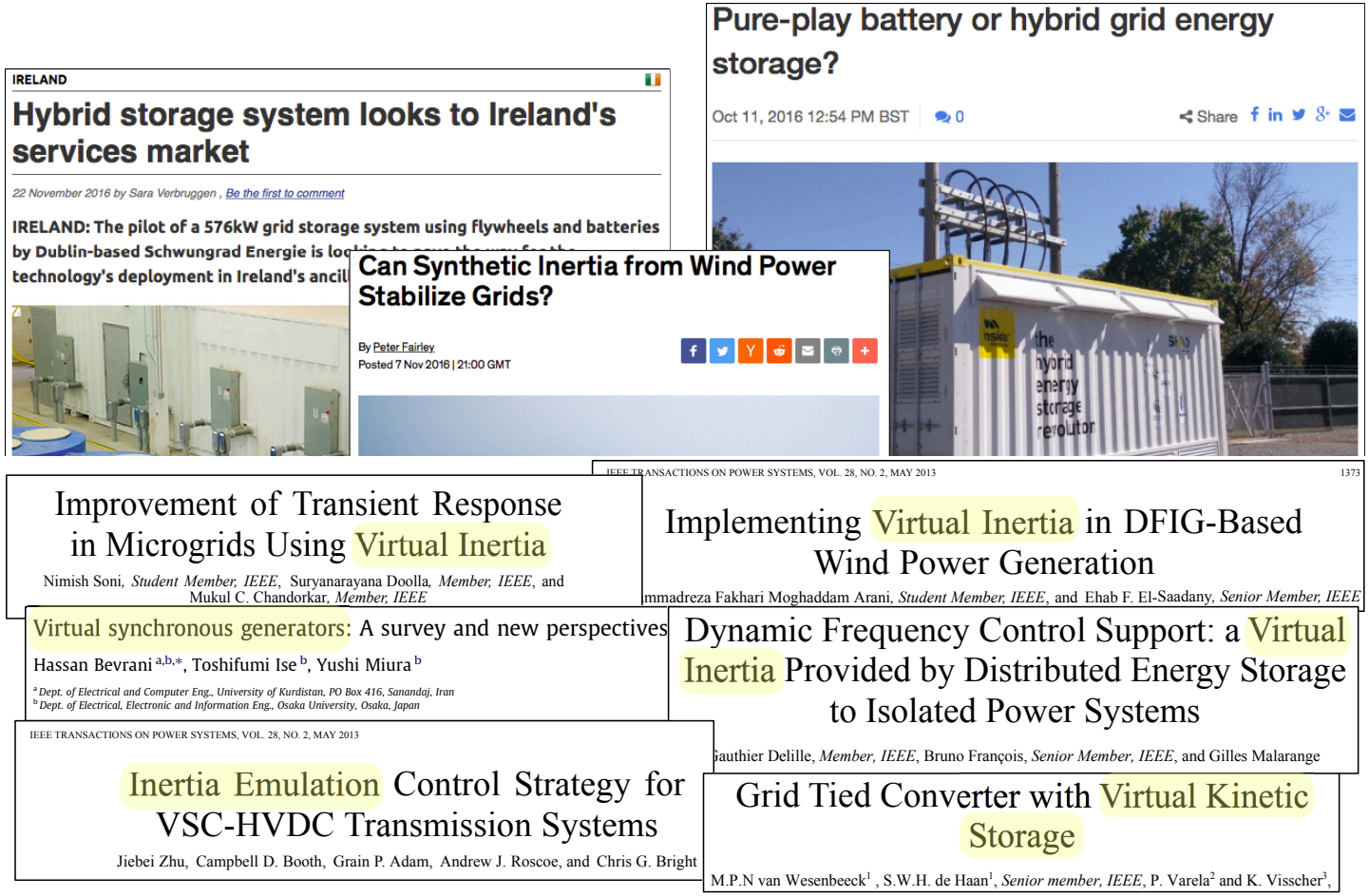
Inertia Emulation Control Strategy for VSC-HVDC Transmission Systems

Jiebei Zhu, Campbell D. Booth, Grain P. Adam, Andrew J. Roscoe, and Chris G. Bright

Grid Tied Converter with Virtual Kinetic Storage

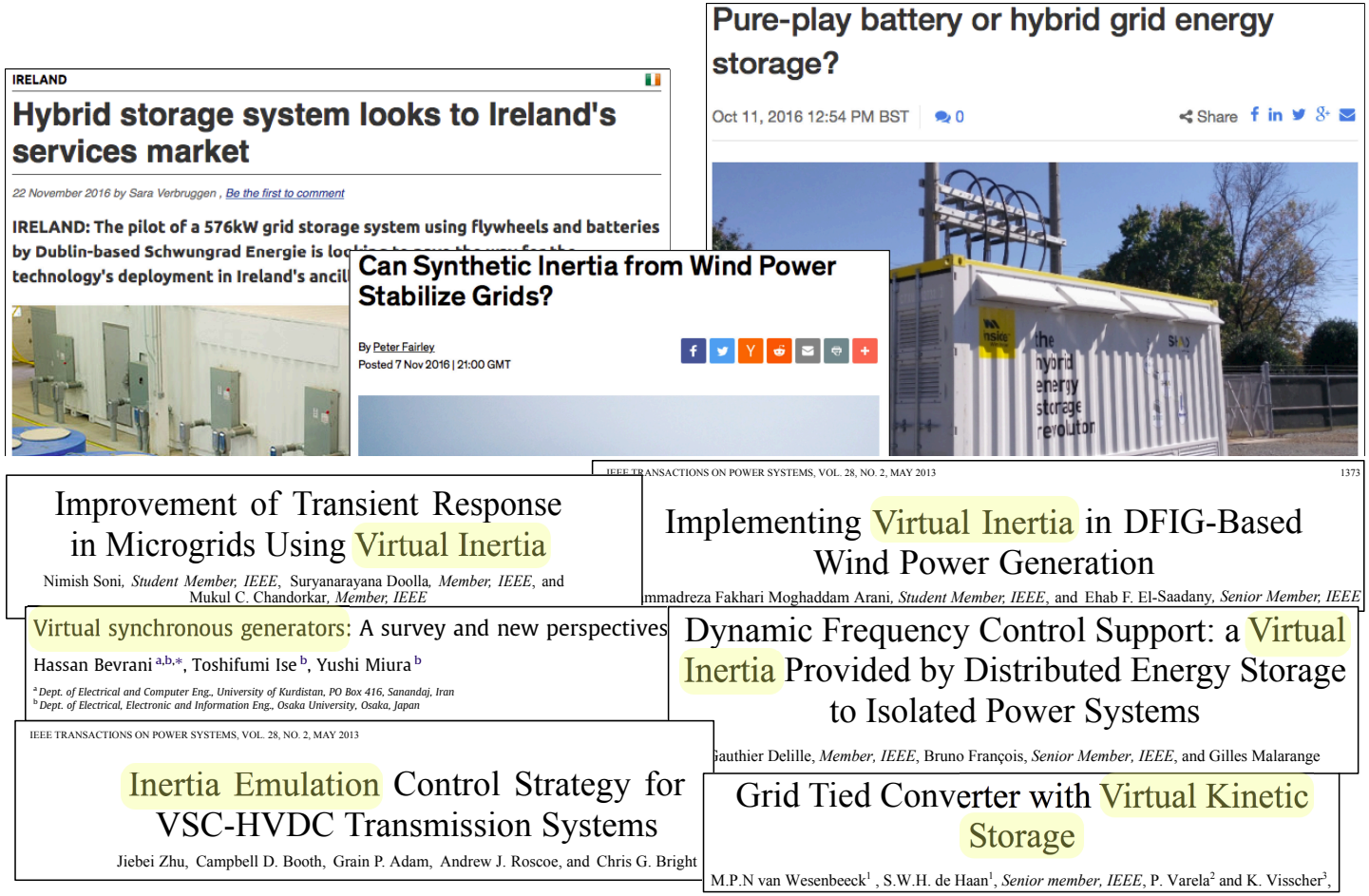
M.P.N van Wesenbeeck[1], S.W.H. de Haan[1], *Senior member, IEEE*, P. Varela[2] and K. Visscher[3],

Naive baseline: virtual inertia emulation



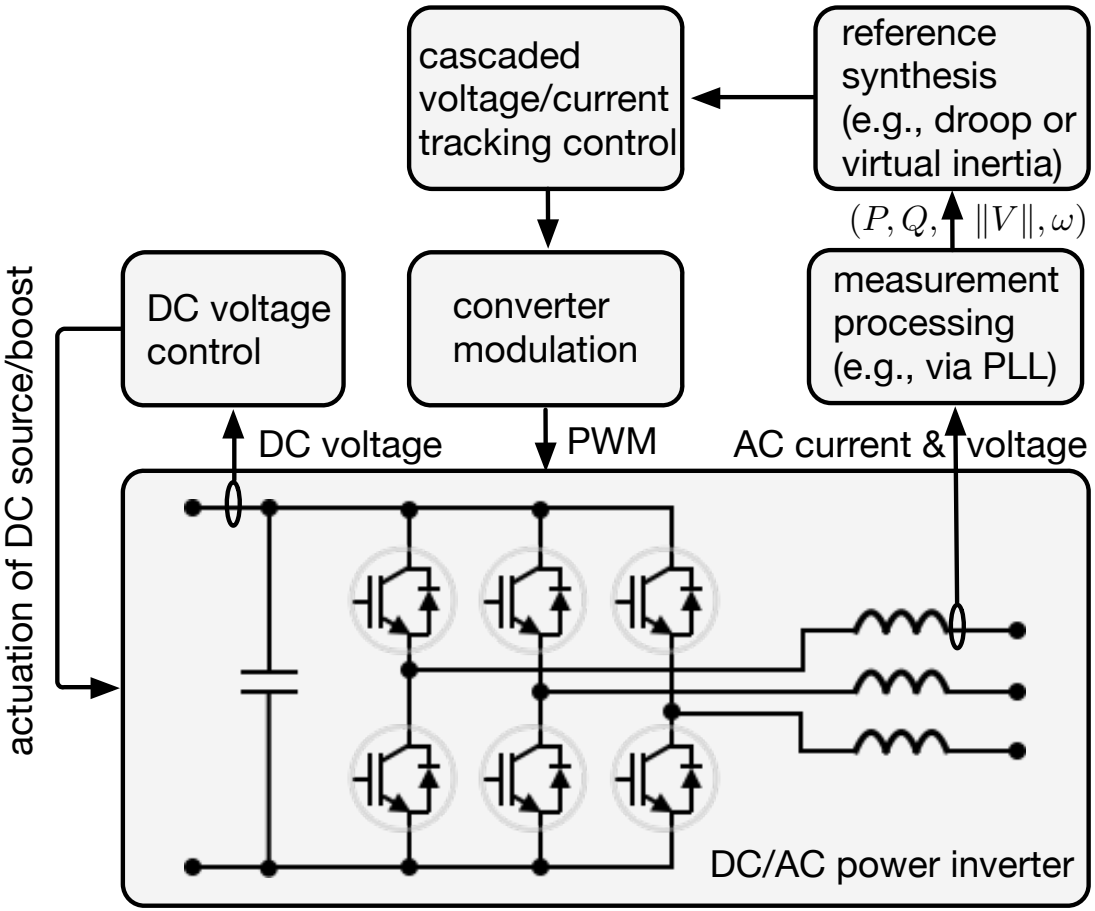
- **PD control** on $\omega(t)$: $\boldsymbol{M}\frac{d}{dt}\omega(t) + \boldsymbol{D}(\omega(t) - \omega_0) = P_{\text{generation}}(t) - P_{\text{demand}}(t)$

Naive baseline: virtual inertia emulation



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

Recall: hierarchical converter control



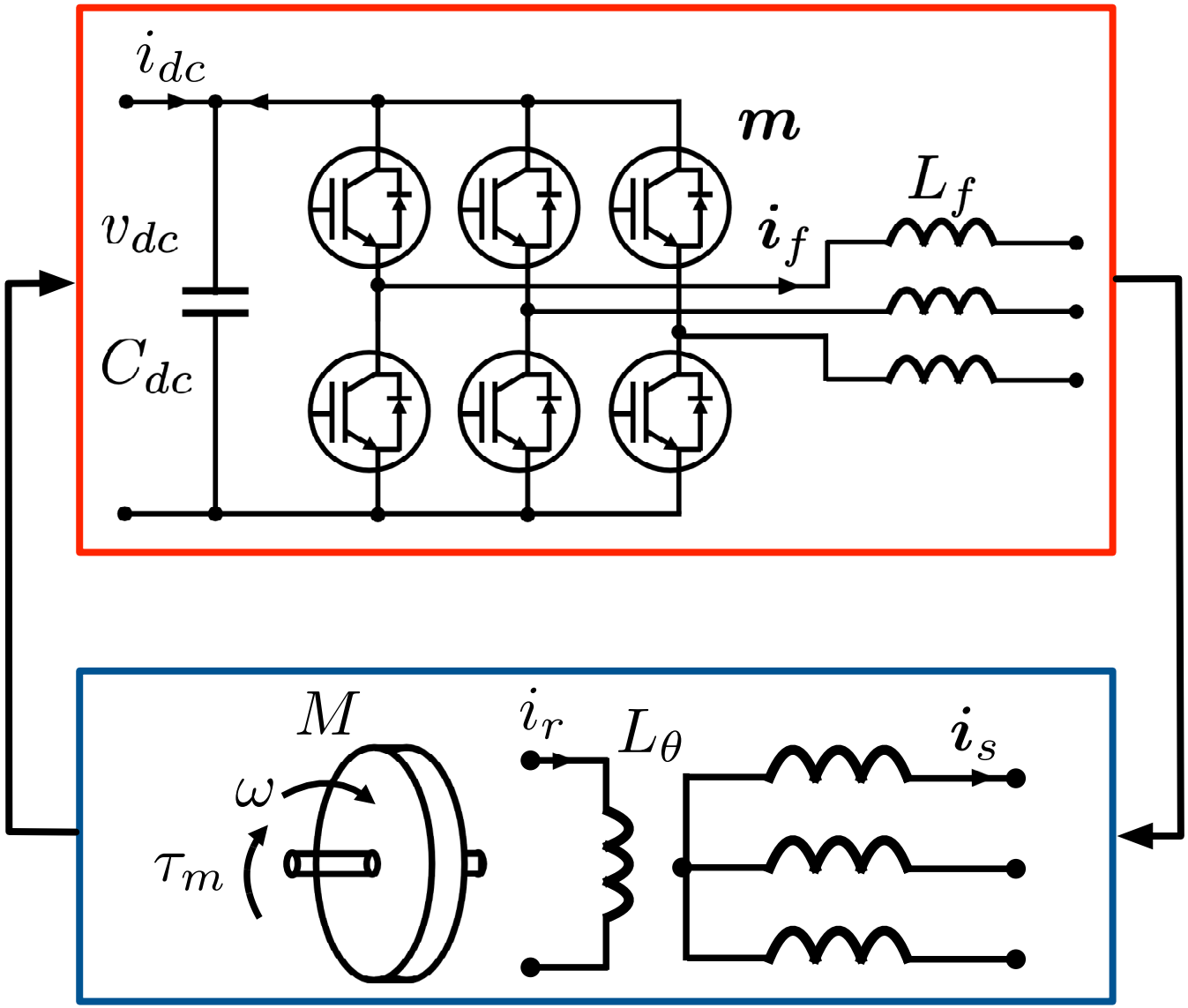
1. acquiring & processing of **AC measurements**
2. synthesis of **references** (voltage/current/power)

   "how would a synchronous generator respond now ?"
3. cascaded PI controllers to **track** references

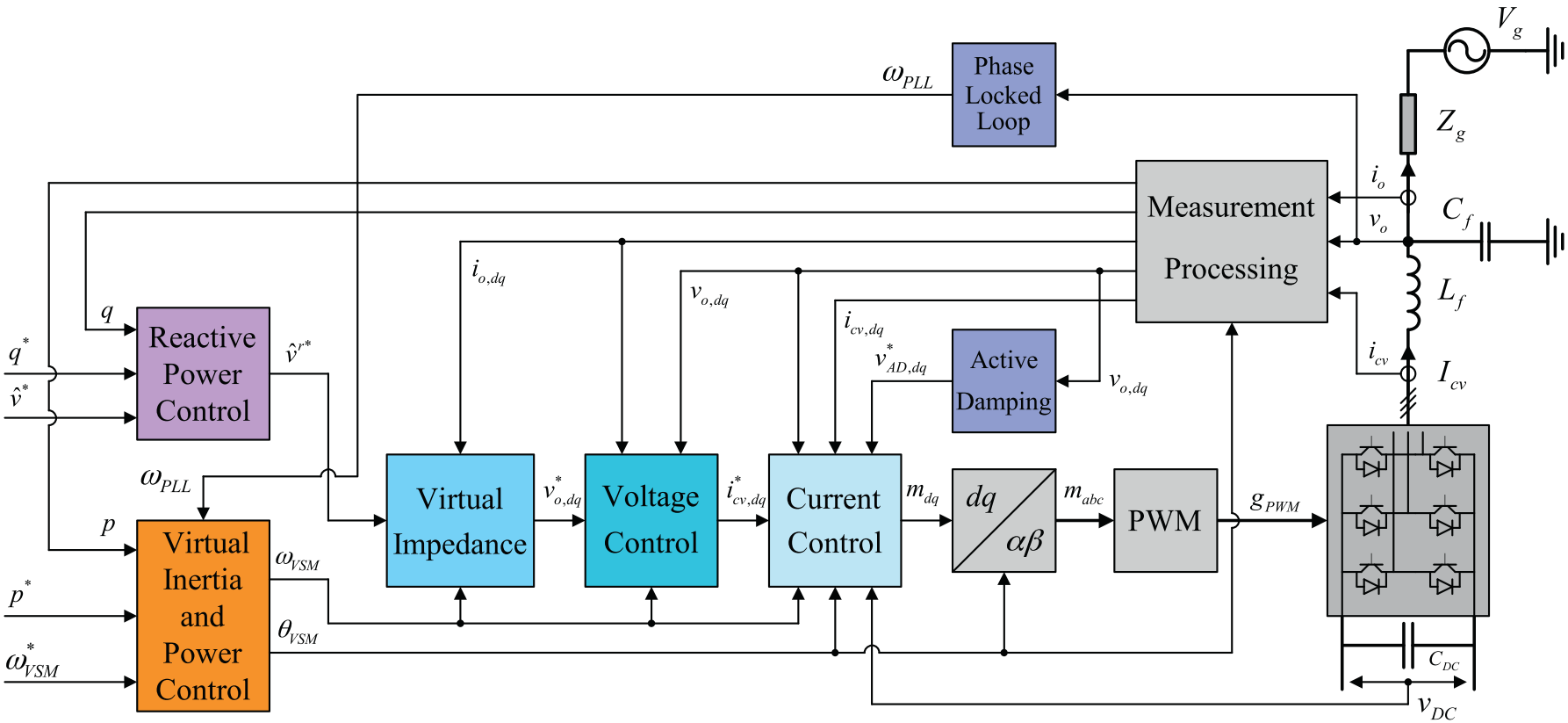
   assumption: no state constraints encountered
4. **actuation** via modulation
5. **energy balancing** via DC-side supply (P-control on DC voltage)

   assumption: unlimited power & instantaneous

Example: virtual machine — conceptual



Example: virtual machine — details



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