ETH zürich

Control of Power Converters in Low-Inertia Power Systems

Florian Dörfler

ETH Zürich

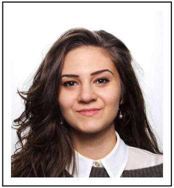
NREL AES Workshop

Acknowledgements

Marcello Colombino

Ali Tayyebi-Khameneh

Dominic Groß



Irina Subotic

Energy Science Center

ETH Foundation Zürich

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SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
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HORIZON 2020

ABB

AIT AUSTRIAN INSTITUTE OF TECHNOLOGY

Further: A. Anta, J.S. Brouillon, G.S. Seo, B. Johnson, M. Sinha, & S. Dhople

Replacing the power system foundation

fuel

– **not sustainable**

renewables

+ **sustainable**

Replacing the power system foundation

fuel

— **not sustainable**

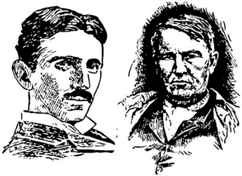
+ **central & dispatchable** generation

renewables

+ **sustainable**

— **distributed & variable** generation

Replacing the power system foundation



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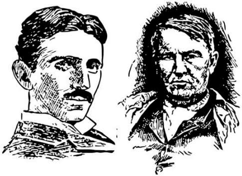

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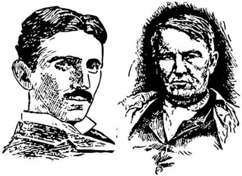


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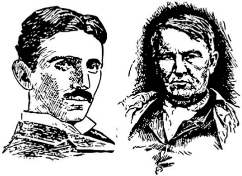

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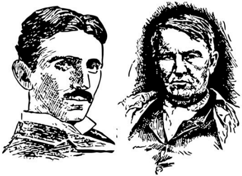

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+ **central & dispatchable** generation

+ **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**

The concerns are not hypothetical

UPDATE REPORT –
BLACK SYSTEM EVENT
IN SOUTH AUSTRALIA ON
28 SEPTEMBER 2016

AEMO
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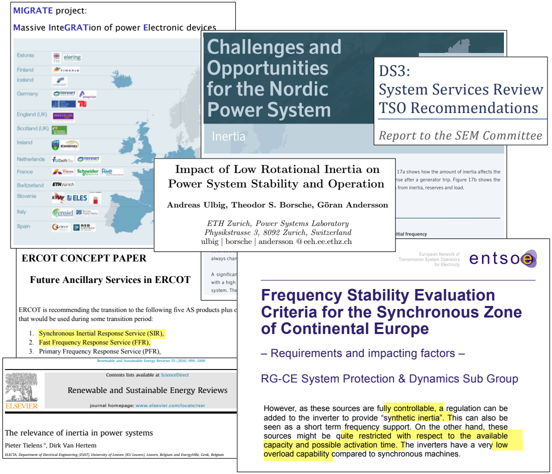

MIGRATE project:

Massive InteGRATion of power Electronic devices

Estonia, Finland, Iceland, Germany, England (UK), Scotland (UK), Ireland, Netherlands, France, Switzerland, Slovenia, Italy, Spain

Challenges and Opportunities for the Nordic Power System

Inertia

DS3: System Services Review TSO Recommendations

Report to the SEM Committee

Impact of Low Rotational Inertia on Power System Stability and Operation

Andreas Ulbig, Theodor S. Borsche, Göran Andersson

ETH Zurich, Power Systems Laboratory
Physikstrasse 3, 8092 Zurich, Switzerland
ulbig | borsche | andersson @eeh.ee.ethz.ch

ERCOT CONCEPT PAPER

Future Ancillary Services in ERCOT

ERCOT is recommending the transition to the following five AS products plus c… that would be used during some transition period:

1. Synchronous Inertial Response Service (SIR),
2. Fast Frequency Response Service (FFR),
3. Primary Frequency Response Service (PFR),

Renewable and Sustainable Energy Reviews 55 (2016) 999–1009

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

The relevance of inertia in power systems

Pieter Tielens*, Dirk Van Hertem

European Network of Transmission System Operators for Electricity

entsoe

Frequency Stability Evaluation Criteria for the Synchronous Zone of Continental Europe

– Requirements and impacting factors –

RG-CE System Protection & Dynamics Sub Group

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Challenges and …

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INDEPENDENT

News › World › Australasia

Tesla's new mega-battery in Australia reacts to outages in 'record' time

One of Australia's biggest power plants suffered a drop in output - the new battery kicked in just 0.14 seconds later

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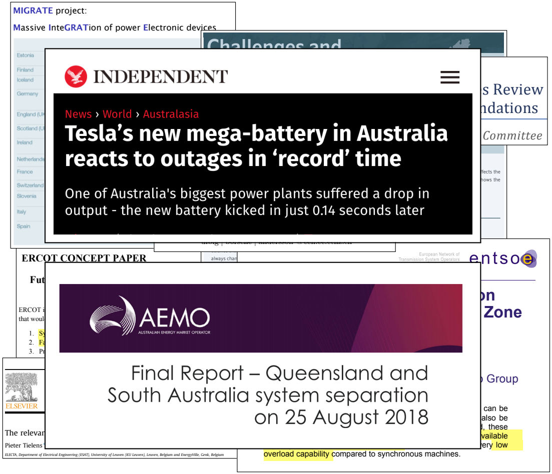

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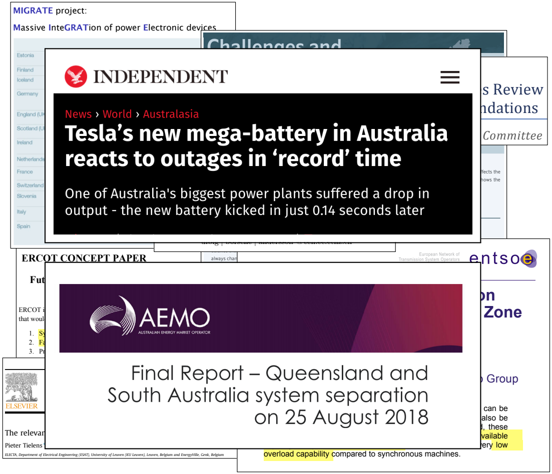
power electronics integration



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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

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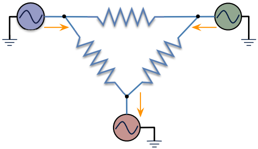
a key unresolved challenge: control of power converters in low-inertia grids

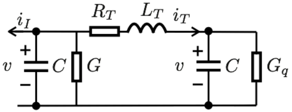
→ industry & power community willing to explore **green-field approach** (see MIGRATE) with ***advanced control*** methods & ***theoretical certificates***

Outline

Basic modeling insights: the network



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



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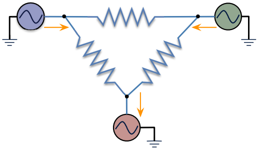

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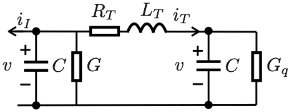

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$$\underbrace{\begin{bmatrix} i_1 \\ \vdots \\ i_n \end{bmatrix}}_{\text{nodal injections}} = \underbrace{\begin{bmatrix} \vdots & \ddots & \vdots & \iddots & \vdots \\ -y_{k1} & \cdots & \sum_{j=1}^{n} y_{kj} & \cdots & -y_{kn} \\ \vdots & \iddots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

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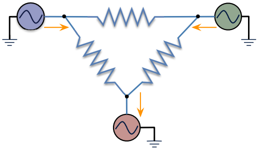

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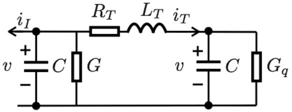

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$$\underbrace{i_k}_{\text{local variable}} = \underbrace{\sum\nolimits_j y_{kj}\,(v_k - v_j)}_{\text{global synchronization}}$$

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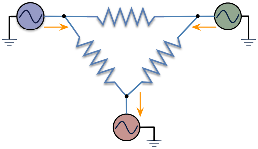

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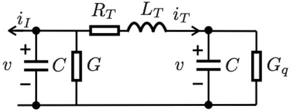

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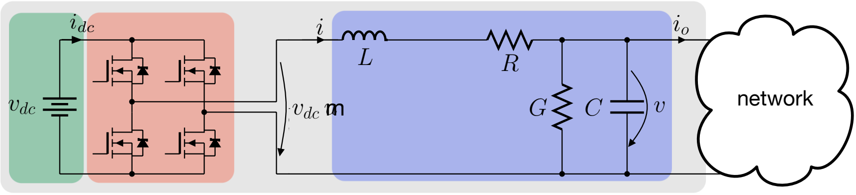
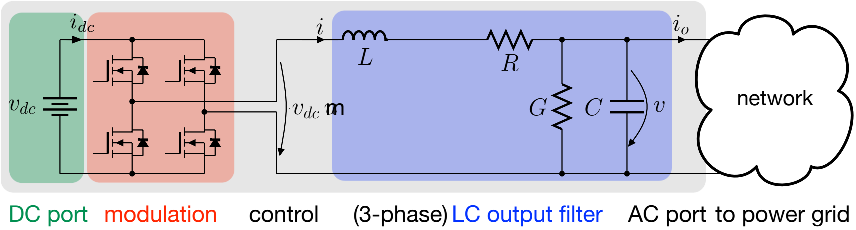
- note: quasi-steady-state **assumption is flawed** in low-inertia systems

Basic modeling insights: the power converter



DC port modulation control (3-phase) LC output filter AC port to power grid

Basic modeling insights: the power converter



- passive ***DC port*** port (i_{dc}, v_{dc}) for energy balance control

→ details mostly neglected today: assume v_{dc} to be stiffly regulated

- ***modulation*** $\equiv$ lossless signal transformer (averaged)

→ controlled switching voltage $v_{dc}m$ with $m \in \left[-\frac{1}{2}, +\frac{1}{2}\right] \times \left[-\frac{1}{2}, +\frac{1}{2}\right]$

- ***LC filter*** to smoothen harmonics with R, G modeling filter/switching losses

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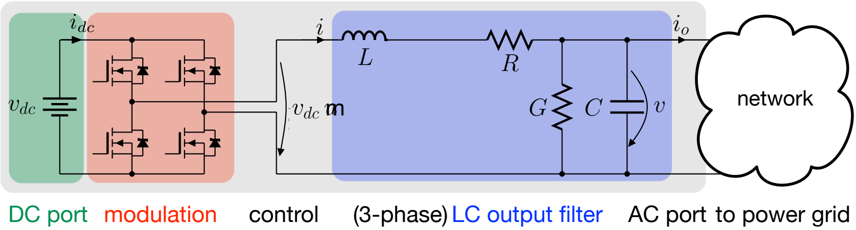

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well actuated, modular, & fast control system $\approx$ **controllable voltage source**

Objectives for power converter control

1. ***synchronous frequency***

$$\frac{d}{dt}\, v_k = \begin{bmatrix} 0 & -\omega_0 \\ \omega_0 & 0 \end{bmatrix} v_k$$

$\sim$ harmonic oscillations at identical ω_0

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3. ***active & reactive power injections***

$$v_k^\top i_{o,k} = p_k^\star \quad , \quad v_k^\top \left[\begin{smallmatrix} 0 & -1 \\ +1 & 0 \end{smallmatrix}\right] i_{o,k} = q_k^\star$$

$\sim$ non-linear but local specification

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3. ***active & reactive power injections*** $\iff$ ***relative voltage angles***

$$v_k^\top\, i_{o,k} = p_k^\star \quad , \quad v_k^\top \left[\begin{smallmatrix} 0 & -1 \\ +1 & 0 \end{smallmatrix}\right] i_{o,k} = q_k^\star$$

$\sim$ non-linear but local specification

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

$\sim$ linear but non-local specification

Objectives for power converter control

1. ***synchronous frequency***

$$\frac{d}{dt} v_k = \begin{bmatrix} 0 & -\omega_0 \\ \omega_0 & 0 \end{bmatrix} v_k$$

$\sim$ harmonic oscillations at identical ω_0

2. ***voltage amplitude***

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

$\sim$ $v^\star$ uniform for ease of presentation

3. ***active & reactive power injections*** $\Longleftrightarrow$ ***relative voltage angles***

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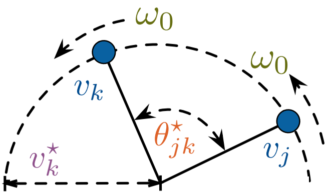
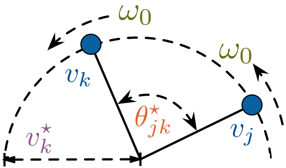
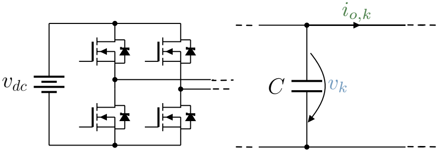


Main control challenges





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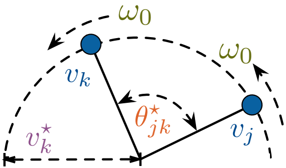
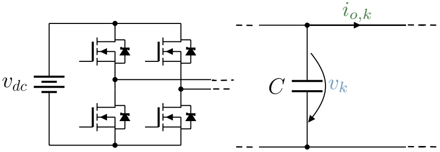
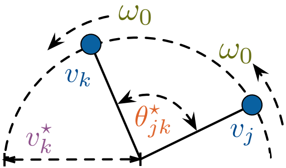
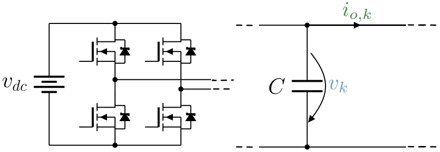




nonlinear objectives $(v^\star_k, \theta^\star_{kj})$ & stabilization of synchronous *limit cycle*

Main control challenges





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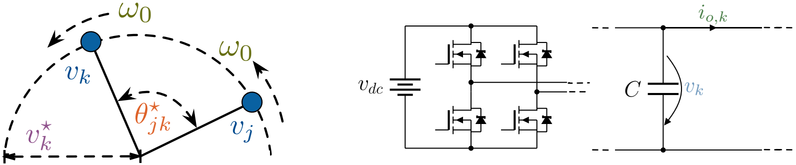

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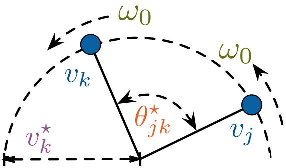

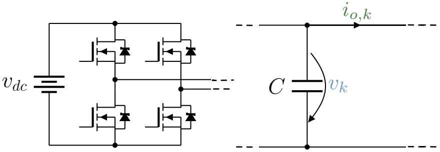

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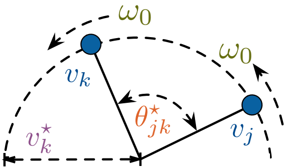

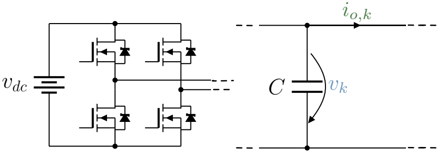

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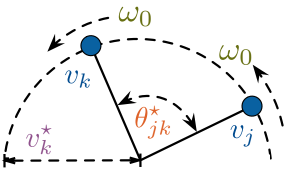

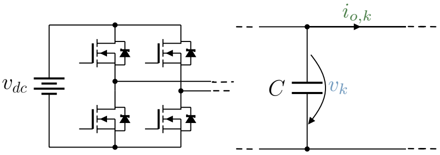

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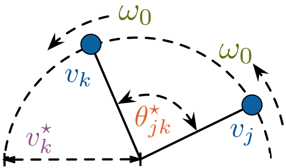

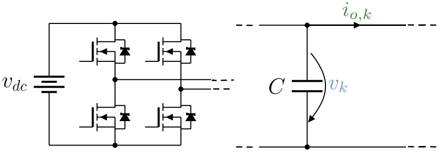

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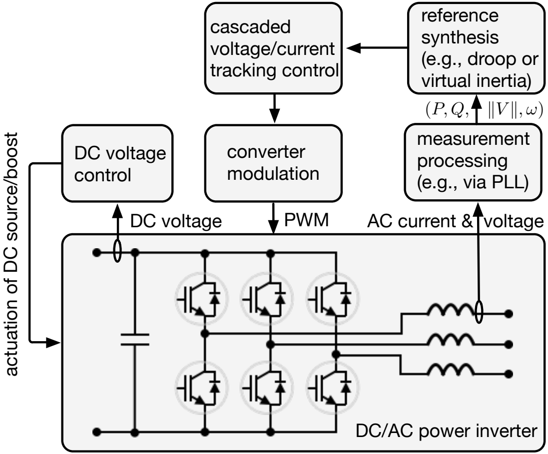
- ↯ ***no time-scale separation*** between slow sources & fast network
- **+** ***fully controllable*** voltage sources & stable ***linear network dynamics***

Naive baseline solution: emulation of virtual inertia

Cartoon of low-level power converter control



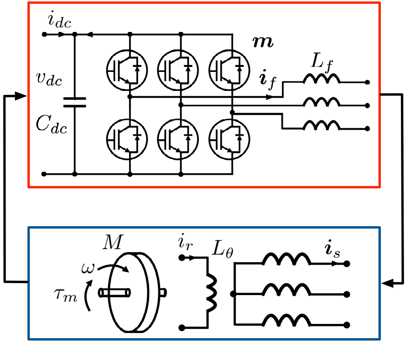
1. acquiring & processing of ***AC measurements***
2. synthesis of ***references***

   "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 fast control of DC-side supply

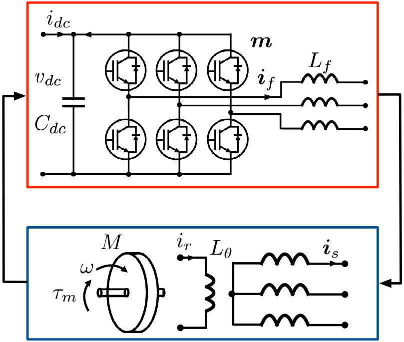
   assumption: unlimited power & instantaneous

Virtual synchronous machine $\equiv$ flywheel emulation



- ***reference model***: detailed model of synchronous generator + controls

Virtual synchronous machine ≡ flywheel emulation



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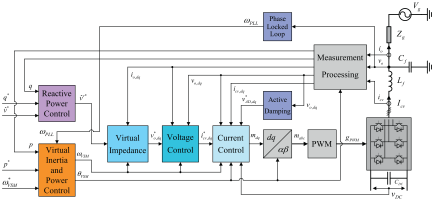

[D'Arco et al., '15]

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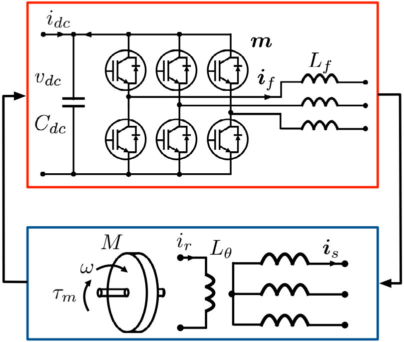

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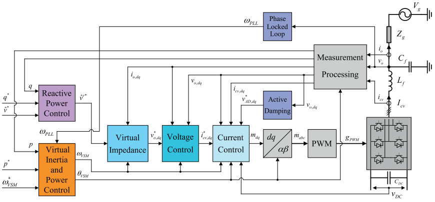

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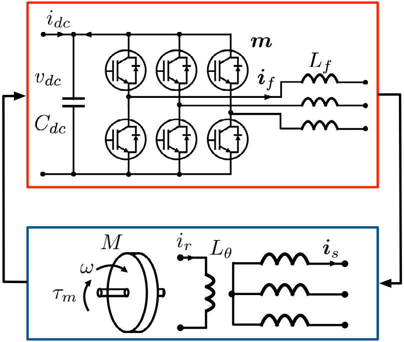

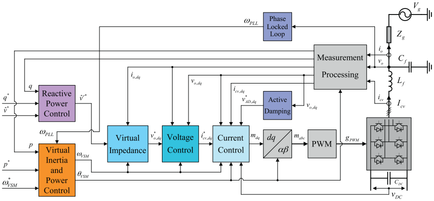

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- converter: **fast** actuation & **no** significant **energy storage**
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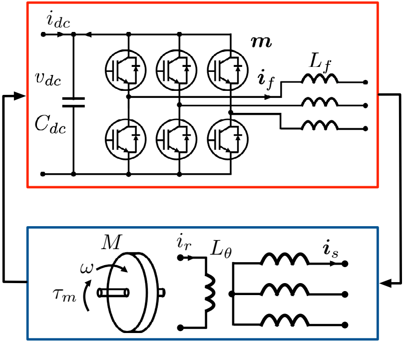

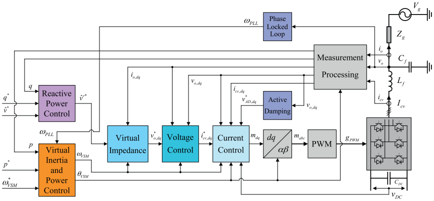

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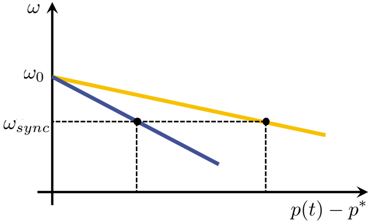
→ **performs very poorly** post-fault

Droop as simplest reference model

[Chandorkar, Divan, Adapa, '93]

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

$$\omega - \omega_0 \;\propto\; p - p^\star$$



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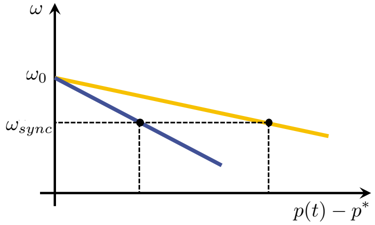

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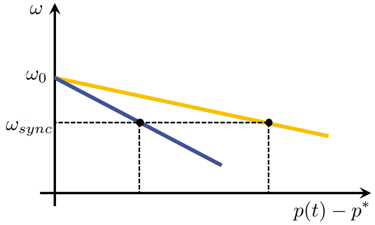

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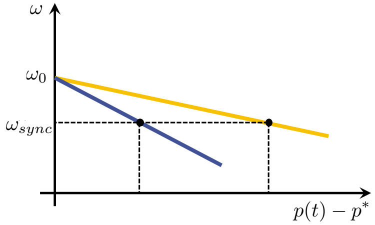

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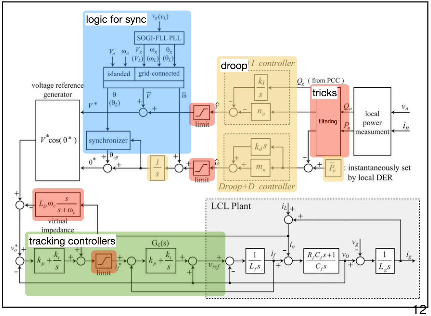

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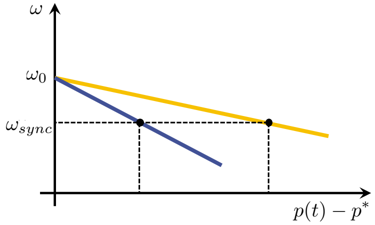

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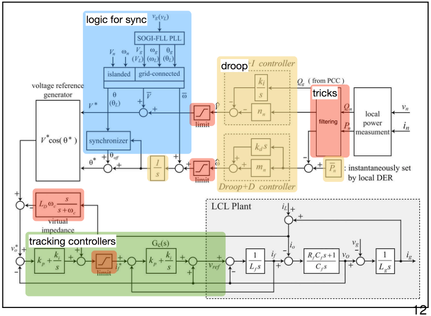
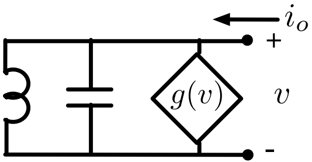
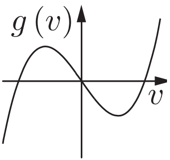


Original **V**irtual **O**scillator **C**ontrol (VOC)

nonlinear & open limit cycle oscillator as reference model





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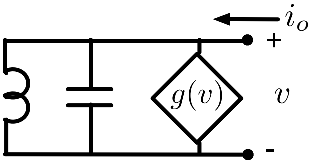

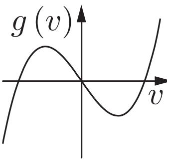

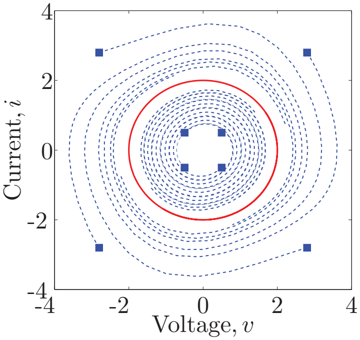

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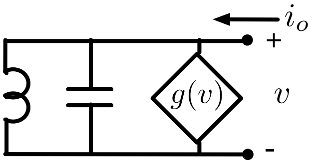
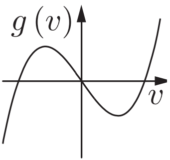


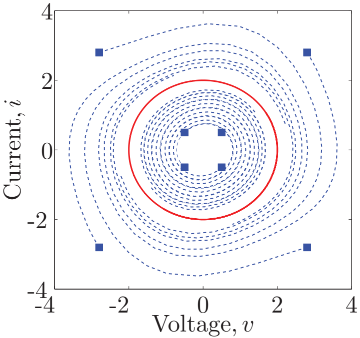


- simplified model amenable to theoretic analysis

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

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

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



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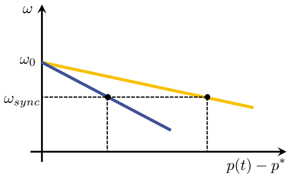
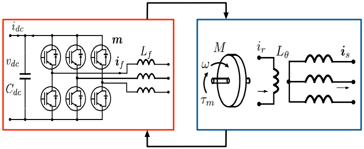


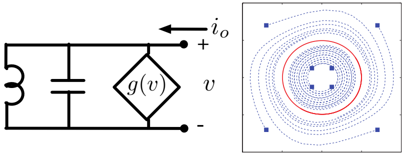
droop control

- \+ good performance near steady state
- − relies on decoupling & small attraction basin



synchronous machine emulation

- \+ backward compatible in nominal case
- − not resilient under large disturbances



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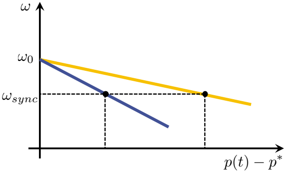

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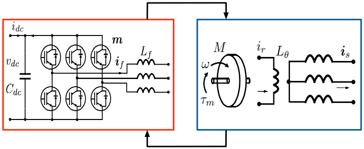

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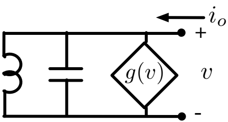

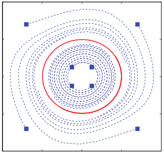

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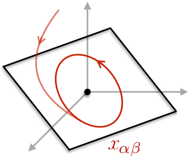
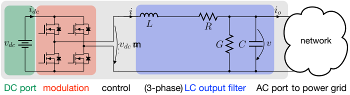


today: dispatchable virtual oscillator

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

Model & control objectives (assumptions can all be generalized)



simplified multi-converter system model

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

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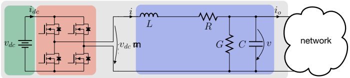

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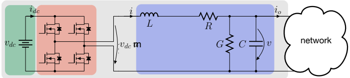

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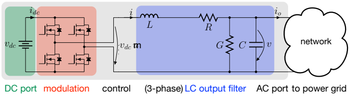

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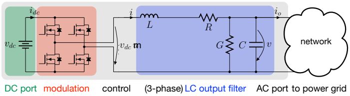

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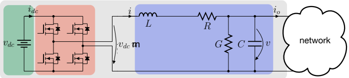

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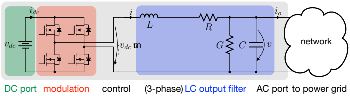

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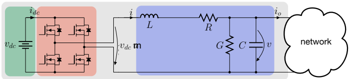

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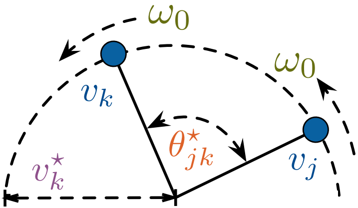
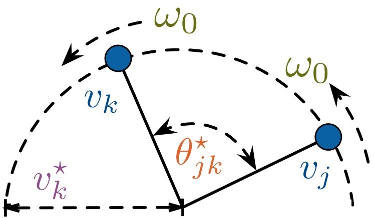
⇔ relative **angles**: $v_j = \begin{bmatrix} \cos(\theta_{jk}^\star) & -\sin(\theta_{jk}^\star) \\ \sin(\theta_{jk}^\star) & \cos(\theta_{jk}^\star) \end{bmatrix} v_k$



Colorful idea: closed-loop target dynamics



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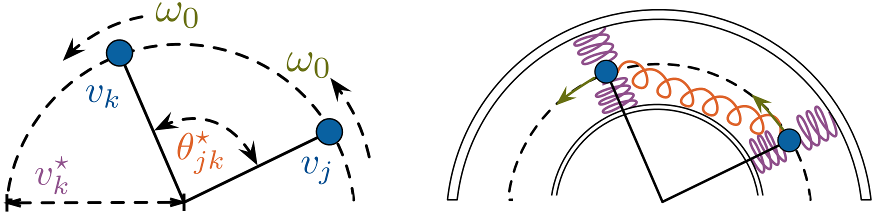

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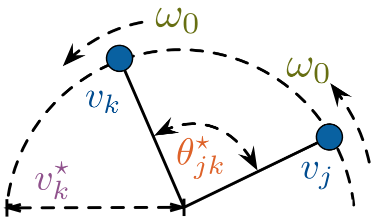

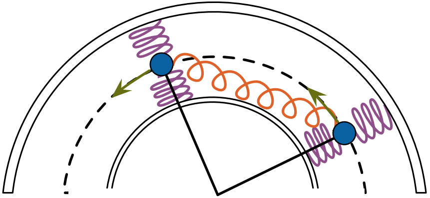

$$\frac{d}{dt}\boldsymbol{v_k} = \underbrace{\begin{bmatrix} 0 & -\omega_0 \\ \omega_0 & 0 \end{bmatrix} \boldsymbol{v_k}}_{\text{rotation at } \omega} + c_2 \cdot \underbrace{\left(\|v_k\|^{\star 2} - \|\boldsymbol{v}_k\|^2 \right) \boldsymbol{v}_k}_{\text{amplitude regulation to } v_k^\star}$$

$$+ \; c_1 \cdot \underbrace{\sum_{j=1}^{n} w_{jk} \left(\boldsymbol{v}_j - \begin{bmatrix} \cos(\theta^\star_{jk}) & -\sin(\theta^\star_{jk}) \\ \sin(\theta^\star_{jk}) & \cos(\theta^\star_{jk}) \end{bmatrix} \boldsymbol{v}_k \right)}_{\text{synchronization to desired relative angles } \theta^\star_{jk}}$$

Decentralized implementation of dynamics

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

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

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

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

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$$\left.\begin{aligned} p^\star_k &= v^{\star 2} \sum_j \frac{r_{jk}(1-\cos(\theta^\star_{jk})) - \omega_0 \ell_{jk} \sin(\theta^\star_{jk})}{r^2_{jk} + \omega^2_0 \ell^2_{jk}} \\ q^\star_k &= -v^{\star 2} \sum_j \frac{\omega_0 \ell_{jk}(1-\cos(\theta^\star_{jk})) + r_{jk} \sin(\theta^\star_{jk})}{r^2_{jk} + \omega^2_0 \ell^2_{jk}} \end{aligned}\right\} \Rightarrow \underbrace{\mathcal{K}_k(\theta^\star)}_{\text{global parameters}} = \underbrace{\frac{1}{v^{\star 2}} R(\kappa) \begin{bmatrix} q^\star_k & p^\star_k \\ -p^\star_k & q^\star_k \end{bmatrix}}_{\text{local parameters}}$$

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

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- **amplitude control** “slower” than **synchronization control**

Details on stability condition

- **power transfer** p_{jk} “small” compared to **network connectivity** λ_2
- **amplitude control** “slower” than **synchronization control**: $c_2/c_1 \ll 1$

e.g., for resistive grid: $$\frac{1}{2}\underbrace{\lambda_2}_{\text{algebraic connectivity}} > \max_k \sum_{j=1}^{n} \frac{1}{v^{\star 2}} \underbrace{|p_{jk}|}_{\text{power transfer}} + \frac{c_2}{c_1} v^{\star}$$

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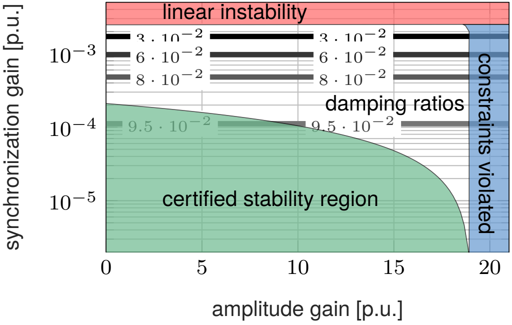

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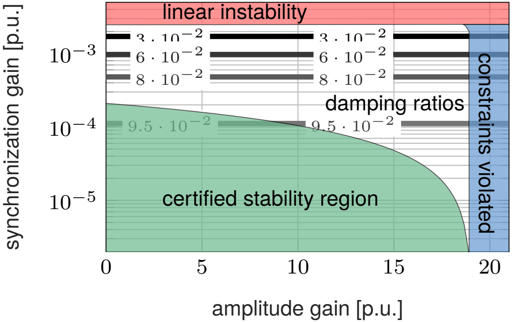

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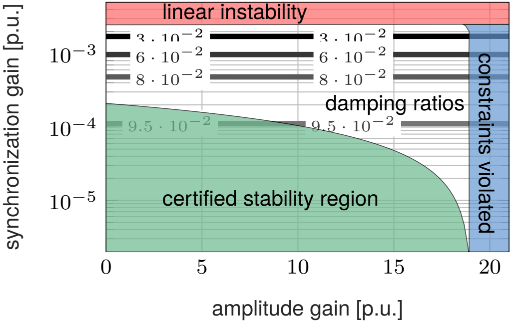

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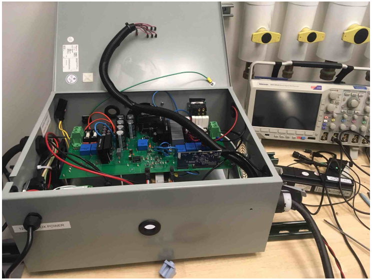
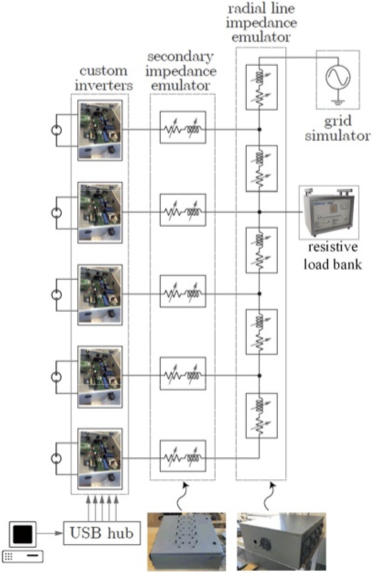
- proof relies on **Lyapunov arg's**
- **conditions can be extended** to line dynamics, LC filter, & inner loops [Subotic, Gross, Colombino, & Dörfler,'19]

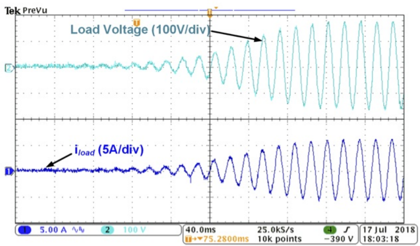
Experimental setup @ NREL



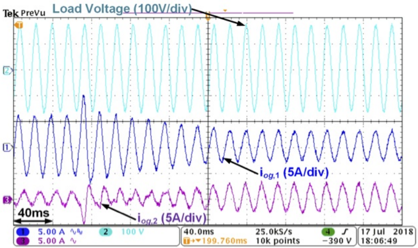


Experimental results

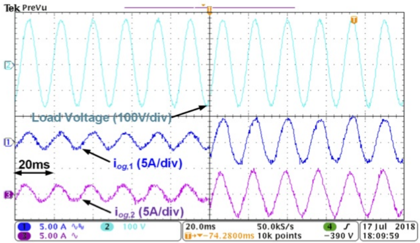
[Seo, Subotic, Johnson, Colombino, Groß, & Dörfler, '19]



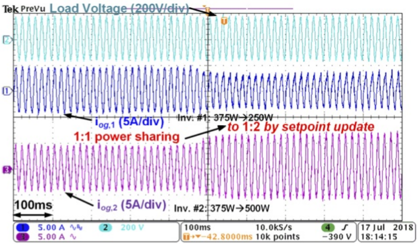
black start of inverter #1 under 500 W load (making use of almost global stability)



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

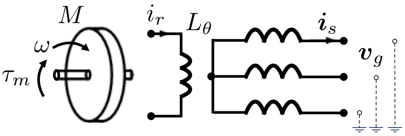


250 W to 750 W load transient with two inverters active



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

Detour: ***duality & matching*** of machines [Arghir & Dörfler,'19]



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

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

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

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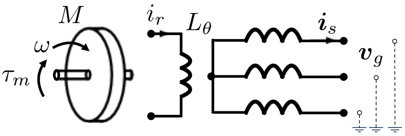

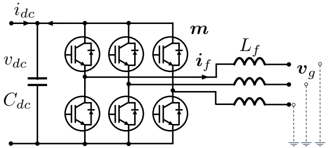

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$$C_\mathrm{dc}\frac{\mathrm{d}v_\mathrm{dc}}{\mathrm{d}t} = -G_\mathrm{dc}v_\mathrm{dc} + i_\mathrm{dc} + \boldsymbol{m}^\top \boldsymbol{i}_f$$

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

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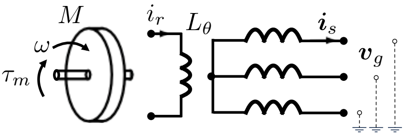

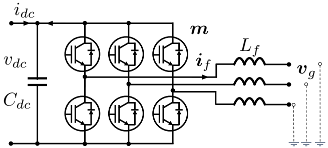

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1. modulation in polar coordinates:

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

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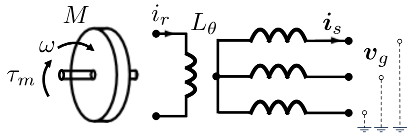

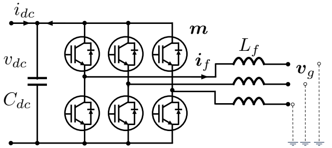

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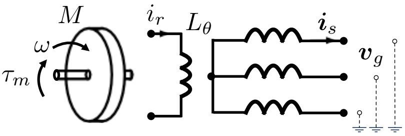

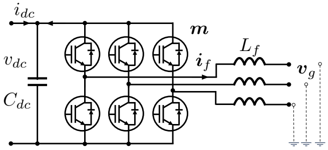

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→ duality: $C_{\mathsf{dc}} \sim M$ is equivalent inertia

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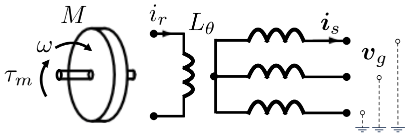

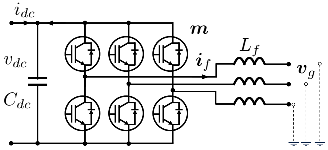

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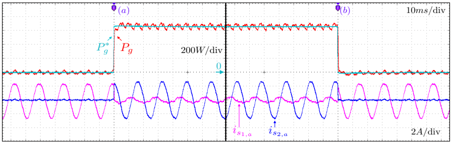

theory & practice: ***robust*** duality $\omega \sim v_{\mathsf{dc}}$

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Comparison(s) of control strategies

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

Simulation-based study of novel control strategies for inverters in low-inertia system: grid-forming and grid-following

Author: Alessandro Crivellaro

Mathias Melby

Comparison of virtual oscillator control and droop control in an inverter-based stand-alone microgrid

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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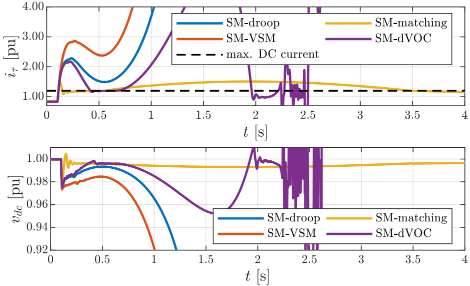
- . . . comparison suggests ***hybrid VOC + matching control*** direction

Comparison of control strategies @AIT



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Frequency Stability of Synchronous Machines and Grid-Forming Power Converters

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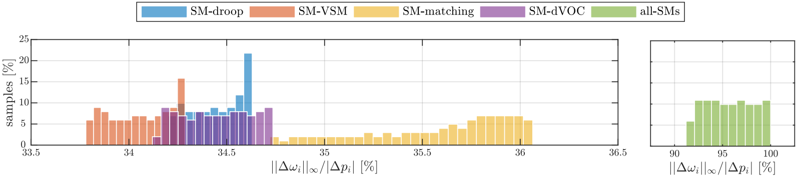

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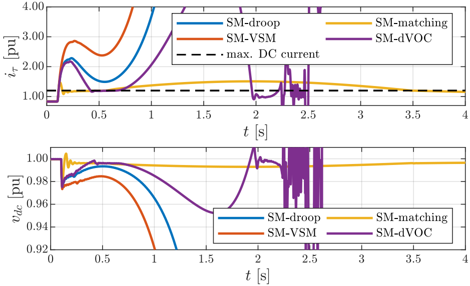

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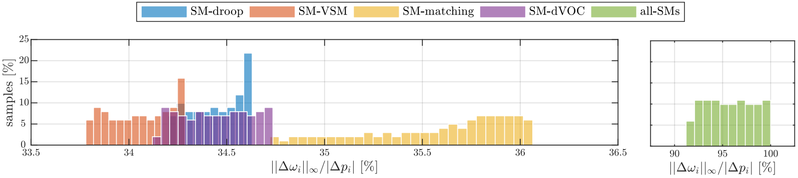

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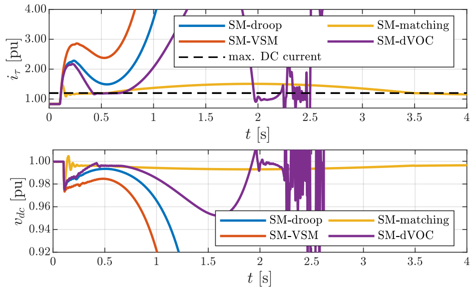

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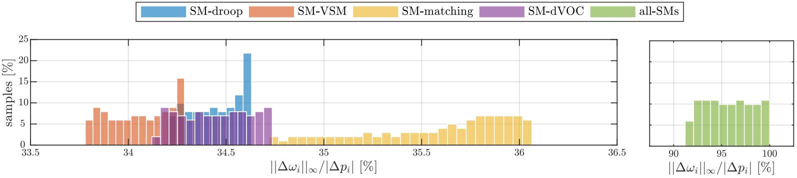
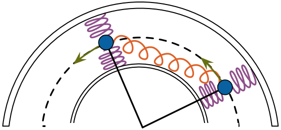
- promising **hybrid control** directions: VOC + matching



Conclusions

Summary

- dispatchable virtual oscillator control
- theoretic analysis & experiments



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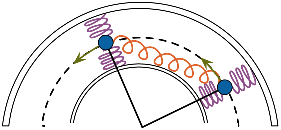

Ongoing & future work

- robustness & compatibility with legacy system
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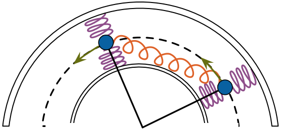

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Hybrid Angle Control and Almost Global Stability of Grid-Forming Power Converters

Ali Tayyebi, Adolfo Anta, and Florian Dörfler

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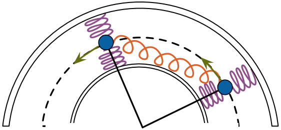

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Main references

M. Colombino, D. Groß, J.S. Brouillon, & F. Dörfler. *Global phase and magnitude synchronization of coupled oscillators with application to the control of grid-forming power inverters*.

→ many other articles on my website (`link`) under keyword "power electronics control"