ETH zürich

Control of Power Converters in Low-Inertia Power Systems

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Acknowledgements

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Further: Gab-Su Seo, Brian Johnson, Mohit Sinha, & Sairaj Dhople

Replacing the power system foundation

fuel & synchronous machines

− **not sustainable**

+ **central & dispatchable** generation

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

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

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

− **slow** actuation & **control**

renewables & power electronics

+ **sustainable**

− **distributed & variable** generation

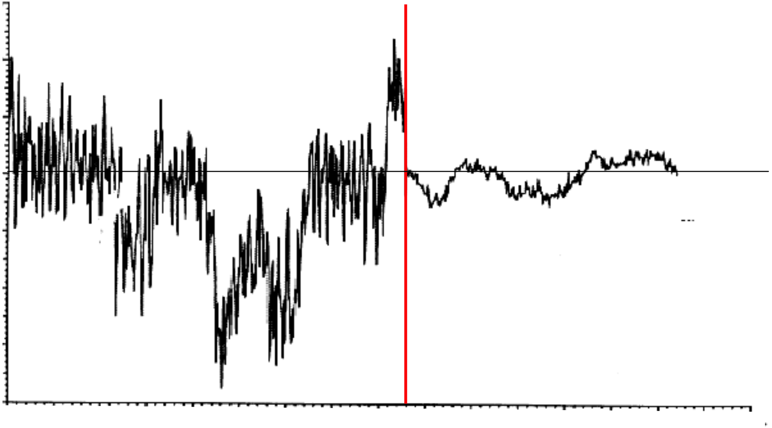
− almost **no energy storage**

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

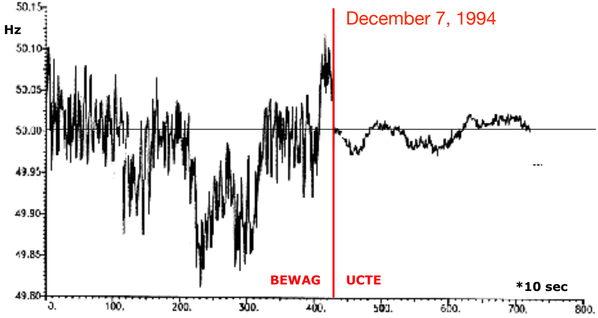
− **fragile** voltage / frequency **control**

+ **fast / flexible / modular control**

What do we see here?



Frequency of West Berlin re-connecting to Europe



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

afterwards connected to European grid based on synchronous generation

The concerns are not hypothetical

issues broadly recognized by TSOs, device manufacturers, academia, agencies, etc.

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

AEMO

AN UPDATE TO THE PRELIMINARY OPERATING INCIDENT
REPORT FOR THE NATIONAL ELECTRICITY MARKET.
DATA ANALYSIS AS AT 5.00 PM TUESDAY 11 OCTOBER 2016.

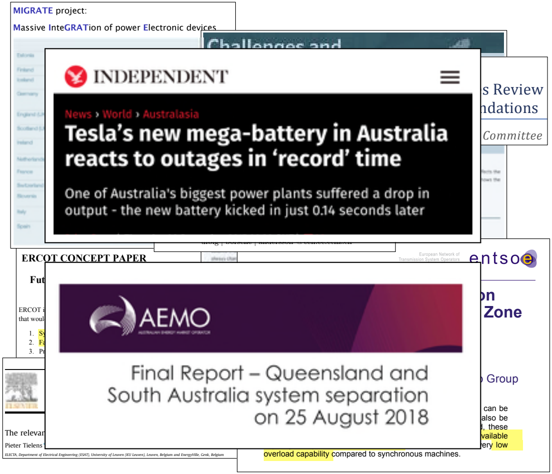
lack of robust control:

"Nine of the 13 wind farms online did not ride through the six voltage disturbances experienced during the event."

between the lines:

conventional system would have been more resilient (?)

obstacle to sustainability:
power electronics integration



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)

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

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

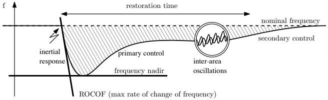
a key unresolved challenge: control of power converters in low-inertia grids

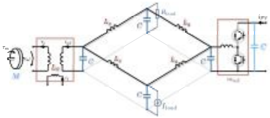
$\rightarrow$ industry & power community willing to explore **green-field approach** (see MIGRATE) with ***advanced control*** methods & ***theoretical certificates***

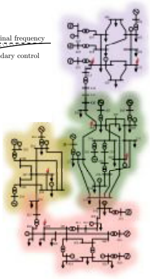
Our research agenda

system-level

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

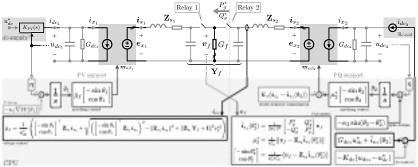


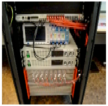


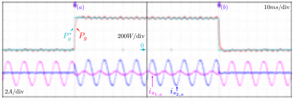


device-level (today)

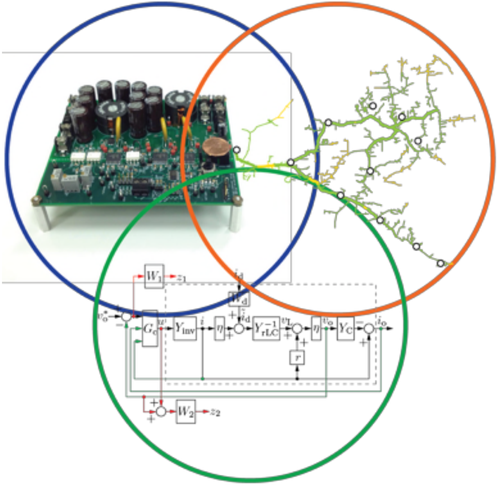
- decentralized nonlinear **power converter control** strategies
- experimental **implementation**, cross-validation, & comparison







Exciting research domain bridging communities



power electronics

power systems

control systems

Outline

Introduction: Low-Inertia Power Systems

Problem Setup: Modeling and Specifications

State of the Art: Comparison & Critical Evaluation

Dispatchable Virtual Oscillator Control

Experimental Validation

Conclusions

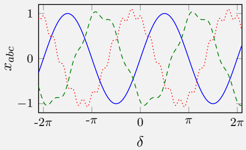
Modeling: signal space in 3-phase AC circuits

three-phase AC

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

periodic with 0 average

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

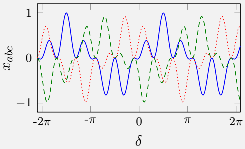


balanced (nearly true)

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

so that

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

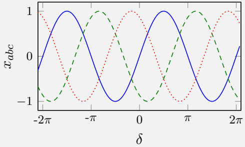


synchronous (desired)

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

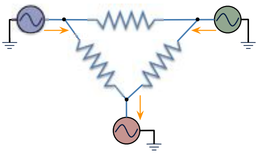
const. freq & amp

$\Rightarrow$ const. in rot. frame

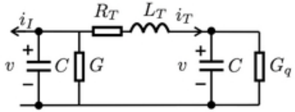


assumption: balanced $\Rightarrow$ 2d-coordinates $x(t) = [x_\alpha(t)\; x_\beta(t)]$ or $x(t) = A(t)e^{i\delta(t)}$

Modeling: the network



interconnecting lines via Π-models & ODEs



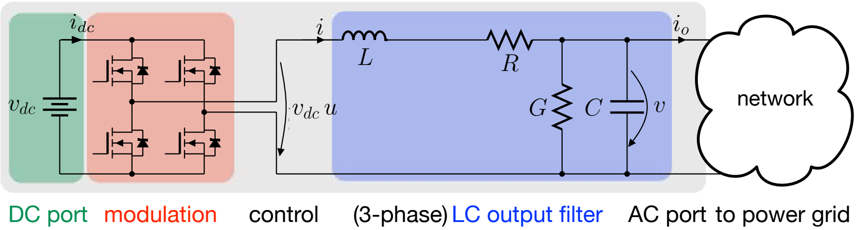
- quasi-steady state ***algebraic model***

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

- salient feature: ***local*** measurement reveal ***global*** information

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

Modeling: the power converter



- ▶ passive ***DC port*** port (i_{dc}, v_{dc}) for energy balance control
- → details neglected today: assume v_{dc} to be stiffly regulated
- ▶ ***modulation*** $\equiv$ lossless signal transformer (averaged)
- → controlled switching voltage $v_{dc}u$ with $u \in \left[-\frac{1}{2}, +\frac{1}{2}\right] \times \left[-\frac{1}{2}, +\frac{1}{2}\right]$
- ▶ ***LC filter*** to smoothen harmonics with R, G modeling filter/switching losses

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

Control objectives in the stationary frame

1. ***synchronous frequency:***

$$\frac{d}{dt} v_k = \begin{bmatrix} 0 & -\omega_0 \\ \omega_0 & 0 \end{bmatrix} v_k \quad \forall\, k \in \mathcal{V} := \{1, \ldots, N\}$$

$\sim$ stabilization at **harmonic oscillation** with **synchronous frequency** ω_0

2. ***voltage amplitude:***

$$\|v_k\| = v^\star \quad \forall\, k \in \mathcal{V} \quad \text{(for ease of presentation)}$$

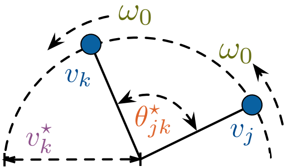
$\sim$ stabilization of voltage **amplitude** $\|v_k\|$

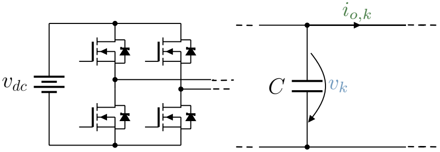
3. ***prescribed power flow:***

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

$\sim$ steady-state **active & reactive power** injections $\{p_k^\star, q_k^\star\}$

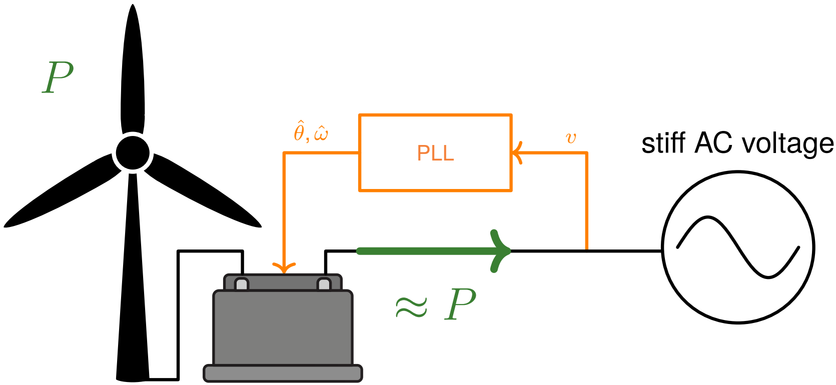
Main control challenges





- ϟ ***nonlinear objectives*** $(v_k^\star, \theta_{kj}^\star)$ & stabilization of a ***limit cycle***
- ϟ ***local set-points:*** voltage/power $(v_k^\star, p_k^\star, q_k^\star)$ but no relative angles $\theta_{kj}^\star$
- ϟ ***decentralized control:*** only local measurements $(v_k, i_{o,k})$ available
- ϟ ***converter physics not resilient:*** no significant storage & state constraints
- ϟ ***no time-scale separation*** between slow sources & fast network
- **+** ***fully controllable*** voltage sources & stable ***linear network dynamics***

Limitations of grid-following control



- ***is good for*** transferring power to a strong grid (what if everyone follows?)
- ***is not good for*** providing a voltage reference, stabilization, or black start
- tomorrow's grid needs ***grid-forming control*** $\equiv$ *emergence of synchronization*

Naive baseline solution: emulation of virtual inertia


IRELAND

Hybrid storage system looks to Ireland's services market

IRELAND: The pilot of a 576kW grid storage system using flywheels and batteries by Dublin-based Schwungrad Energie is loo… technology's deployment in Ireland's ancil…

Pure-play battery or hybrid grid energy storage?

Oct 11, 2016 12:54 PM BST

Can Synthetic Inertia from Wind Power Stabilize Grids?

By Peter Fairley

Posted 7 Nov 2016 | 21:00 GMT

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

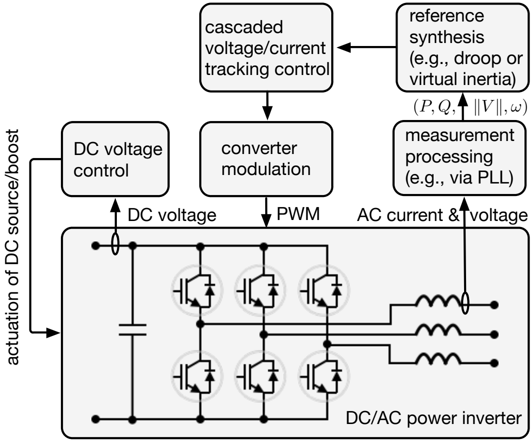
Inertia Emulation Control Strategy for VSC-HVDC Transmission Systems

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],

Standard approach to converter control

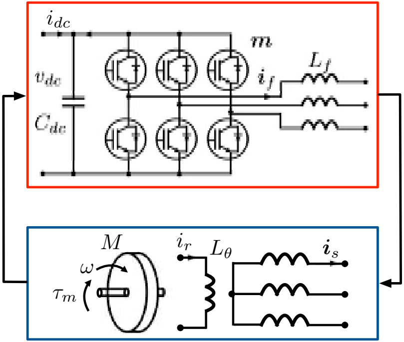


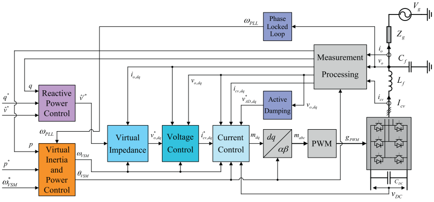
1. acquiring & processing of ***AC measurements***
2. synthesis of ***references*** (voltage/current/power)

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

$\rightarrow$ tight & fast DC-side control

Virtual synchronous machine ≡ flywheel emulation





[D'Arco et al., '15]

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

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

→ robust implementation requires tricks

→ good ***nominal performance*** but poor post-fault behavior → ***not resilient***

→ **poor fit**: converter ≠ flywheel

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

  – machine: **slow** actuation & significant **energy storage**

→ **over-parametrized** & ignores **limits**

→ issues can be partially alleviated via proper nonlinear control [Arghir et al. '17, '19]

Droop as simplest reference model

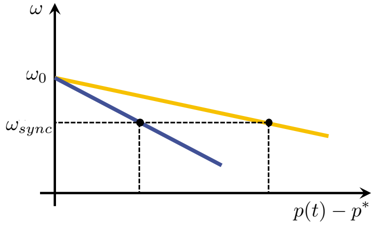
[Chandorkar, Divan, Adapa, '93]

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

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

- ***voltage control*** via $q - \|v\|$ droop control:

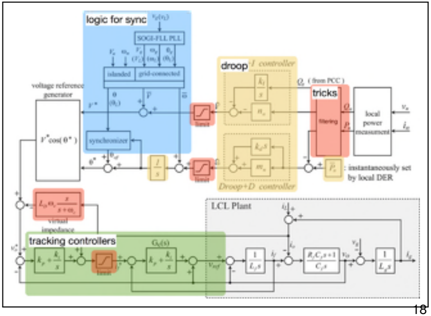
$$\frac{d}{dt}\|v\| = -c_1(\|v\| - v^\star) - c_2(q - q^\star)$$



→ direct control of (p, ω) and $(q, \|v\|)$ **assuming they are independent** (approx. true only near steady state)

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

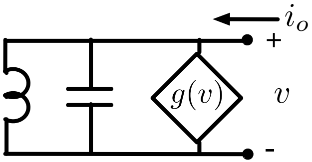
→ ***performance:*** good near steady state but narrow region of attraction

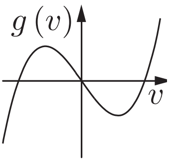


Virtual Oscillator Control (VOC)

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

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



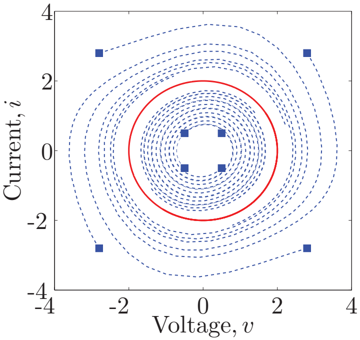


- simplified model amenable to theoretic analysis

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

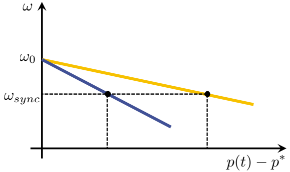
- in practice proven to be ***robust mechanism*** with performance superior to droop & others

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



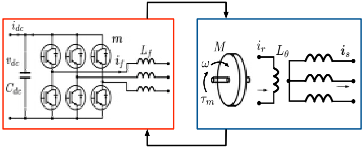
[J. Aracil & F. Gordillo, '02], [Torres, Hespanha, Moehlis, '11], [Johnson, Dhople, Krein, '13], [Dhople, Johnson, Dörfler, '14]

Comparison of grid-forming control [Tayyebi et al., '19]



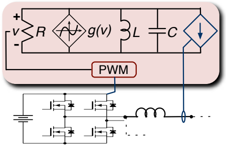
droop control

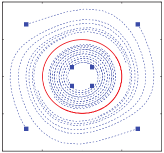
- \+ good performance near steady state
- − relies on decoupling & small attraction basin



synchronous machine emulation

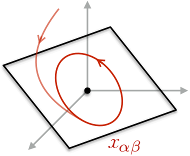
- \+ backward compatible in nominal case
- − not resilient under large disturbances





virtual oscillator control (VOC)

- \+ robust & almost globally synchronization
- − cannot meet amplitude/power specifications

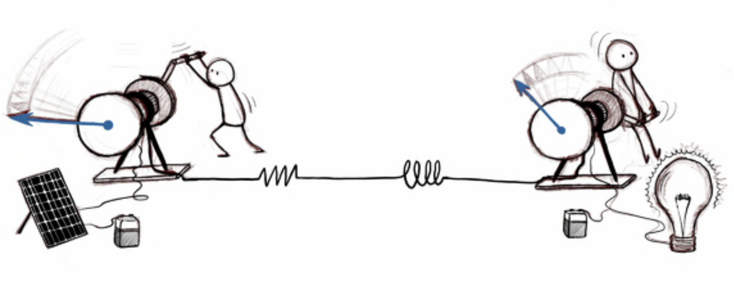


today: foundational control approach

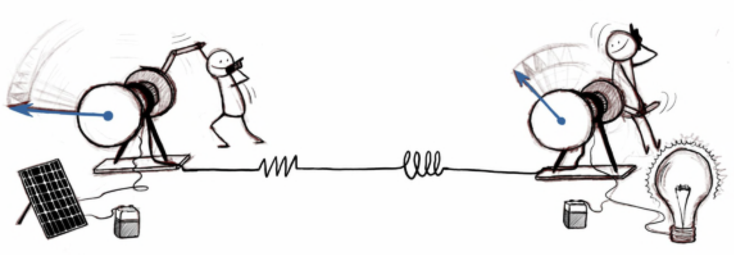
[Colombino, Groß, Brouillon, & Dörfler, '17, '18,'19]
[Seo, Subotic, Johnson, Colombino, Groß, & Dörfler, '18]

Cartoon summary of today's approach

Conceptually, inverters are oscillators that have to synchronize

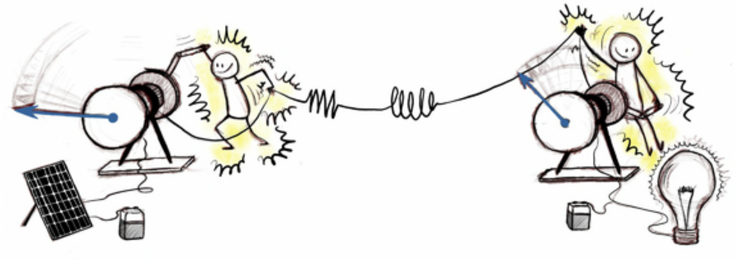


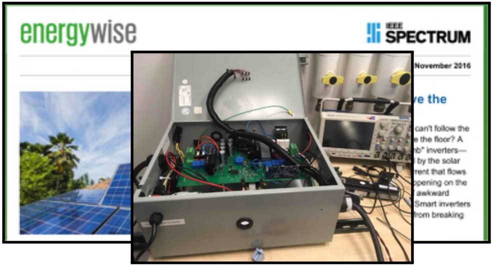
Hypothetically, they could sync by communication (not feasible)



Cartoon summary of today's approach

Colorful idea: inverters sync through physics & clever local control



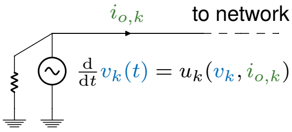


theory: sync of coupled oscillators & nonlinear decentralized control

power systems/electronics ***experiments*** @NREL show superior performance

Recall problem setup

1. simplifying assumptions (will be removed later)



- converter ≈ controllable voltage source
- grid ≈ quasi-static: $\ell \frac{d}{dt} i + ri \approx (\mathrm{j}\omega_0 \ell + r) i$
- lines ≈ homogeneous $\kappa = \tan(\ell_{kj}/r_{kj}) \; \forall k, j$

2. fully decentralized control of converter terminal voltage & current

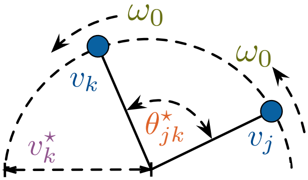
- ↯ set-points for relative angles $\{\theta^\star_{jk}\}$
- ↯ nonlocal measurements v_j
- ↯ grid & load parameters

- ✓ local measurements $(v_k, i_{o,k})$
- ✓ local set-points $(v^\star_k, p^\star_k, q^\star_k)$

3. control objective

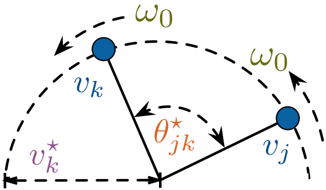
stabilize desired quasi steady state

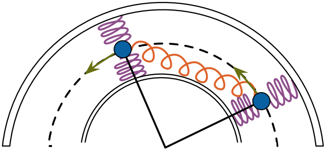
(synchronous, 3-phase-balanced,
and meet set-points in nominal case)



Colorful idea for closed-loop target dynamics

$$\frac{d}{dt} v_k = \underbrace{\begin{bmatrix} 0 & -\omega_0 \\ \omega_0 & 0 \end{bmatrix} v_k}_{\text{rotation at } \omega_0} + c_1 \cdot \underbrace{e_{\theta,k}(v)}_{\text{synchronization}} + c_2 \cdot \underbrace{e_{\|v\|,k}(v_k)}_{\text{amplitude regulation}}$$





synchronization:

$$e_{\theta,k}(v) = \sum_{j=1}^{n} w_{jk} \left(v_j - R(\theta^\star_{jk}) v_k \right)$$

amplitude regulation:

$$e_{\|v\|,k}(v_k) = \left(v^{\star 2} - \|v_k\|^2 \right) v_k$$

Decentralized implementation of target dynamics

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

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

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

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

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

Main results

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

$$\frac{d}{dt}v_k = \underbrace{\begin{bmatrix} 0 & -\omega_0 \\ \omega_0 & 0 \end{bmatrix} v_k}_{\text{rotation at } \omega_0} + c_1 \cdot \underbrace{\sum_{j=1}^{n} w_{jk}(v_j - R(\theta^\star_{jk})v_k)}_{\text{synchronization with global knowledge}} + c_2 \cdot \underbrace{(v^{\star 2} - \|v_k\|^2)\, v_k}_{\text{local amplitude regulation}}$$

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

2. ***almost global stability*** result:

If the $\boxed{\dots}$ condition holds, the system is **almost globally asymptotically stable** with respect to a **limit cycle** corresponding to a **pre-specified** solution of the **AC power-flow** equations at a **synchronous** frequency ω_0.

Main results cont'd

3. certifiable, sharp, and intuitive ***stability conditions***:

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

e.g., for resistive grid:

$$\frac{1}{2} \underbrace{\lambda_2}_{\text{algebraic connectivity}} > \max_k \sum_{j=1}^{n} \frac{1}{v^{\star 2}} \underbrace{|p_{jk}|}_{\text{power transfer}} + \frac{c_2}{c_1} v^\star$$

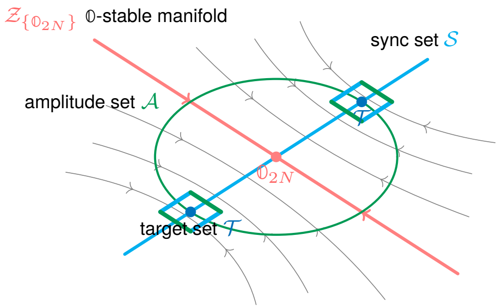
4. connection to ***droop control*** revealed in polar coordinates (for inductive grid):

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

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

Proof sketch for algebraic grid: Lyapunov & center manifold

Lyapunov function: $V(v) = \frac{1}{2}\text{dist}(v, \mathcal{S})^2 + \frac{c_2}{v^{\star 2}} \sum_k \left(v^{\star 2} - \|v_k\|^2\right)^2$



$\mathcal{T} \cup \mathbb{0}_{2N}$ is globally attractive

$$\lim_{t\to\infty} \|v(t)\|_{\mathcal{T}\cup\mathbb{0}_{2N}} = 0$$

$\mathcal{T}$ is stable

$$\|v(t)\|_{\mathcal{T}} \leq \chi(\|v_0\|_{\mathcal{T}})$$

$\mathcal{T}$ is almost globally attractive

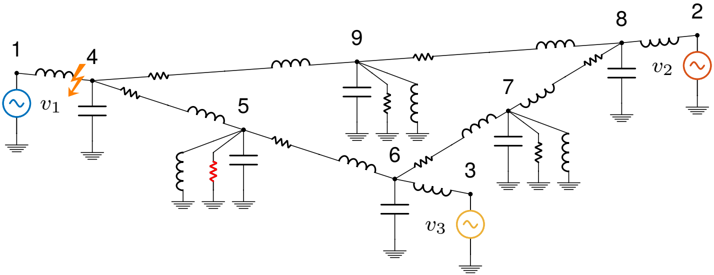
$\mathbb{0}_{2N}$ exponentially unstable

$\implies \mathcal{Z}_{\{\mathbb{0}_{2N}\}}$ has measure zero

$\forall v_0 \notin \mathcal{Z}_{\{\mathbb{0}_{2N}\}} : \lim_{t\to\infty} \|v(t)\|_{\mathcal{T}} = 0$

stability & almost global attractivity $\implies$ ***almost global asymptotic stability***

Case study: IEEE 9 Bus system



t = 0 s: black start of three inverters

- **initial state:** $\|v_k(0)\| \approx 10^{-3}$
- **convergence** to **set-point**

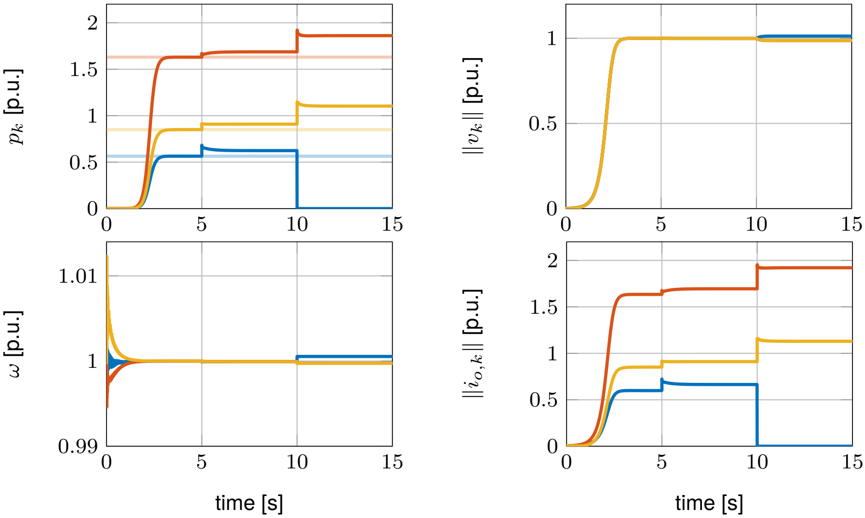
t = 5 s: load step-up

- 20% **load increase** at bus 5
- consistent **power sharing**

t = 10 s: loss of inverter 1

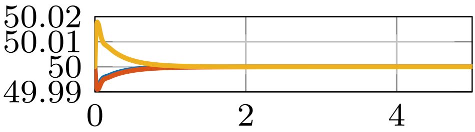
- the **remaining** inverters **synchronize**
- they **supply** the load **sharing power**

Simulation of IEEE 9 Bus system

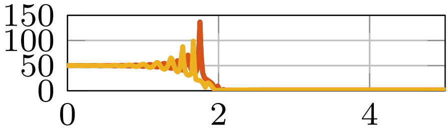


Dropping assumptions: dynamic lines

control gains $\sim 1.8 \cdot 10^{-4}$



control gains $\sim 1.8 \cdot 10^{-3}$



re-do the math leading to updated condition:
amplitude control slower than **sync control**
slower than line dynamics

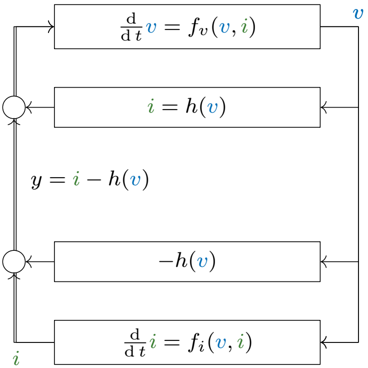
observations

- inverter control **interferes** with the line dynamics
- controller needs to be artificially **slowed down**
- recognized problem
  [Vorobev, Huang, Hosaini, & Turitsyn,'17]

"networked control" reason

- **communication through currents** to infer voltages
- very inductive lines **delay** the information transfer
- the controller must be **slow** in very inductive networks

Proof sketch for dynamic grid: perturbation-inspired Lyapunov



Individual Lyapunov functions

- slow system: $V(v)$ for $\frac{d}{dt} v = f_v(v, h(v))$
- fast system: $W(y)$ for $\frac{d}{dt} y = f_i(v, y + h(v))$ where $\frac{d}{dt} v = 0$ & coordinate $y = i - h(v)$

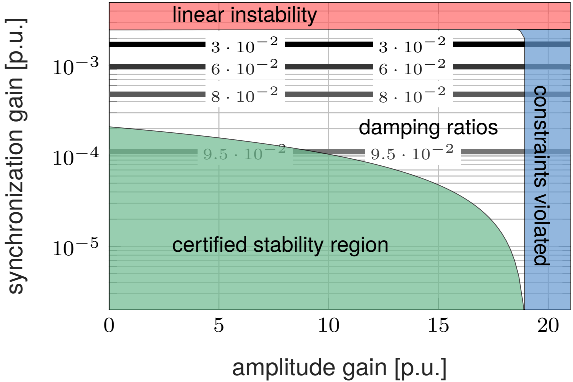
Lyapunov function for the full system

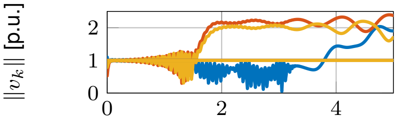
- $\nu(x) = dW(i - h(v)) + (1 - d)V(v)$ where $d \in [0, 1]$ is free convex coefficient
- $\frac{d}{dt} \nu(x)$ is decaying under stability condition

Almost global asymptotic stability

- $\mathcal{T}' \cup \{\mathbb{0}_n\}$ globally attractive & $\mathcal{T}'$ stable
- $\mathcal{Z}_{\{\mathbb{0}_n\}}$ has measure zero

Evaluation of stability conditions





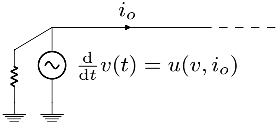
increase of control gains by factor 10

⇒ oscillations, overshoots, & instability

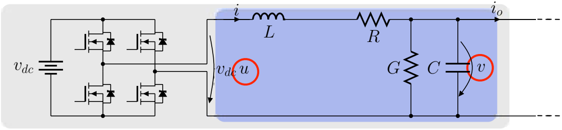
⇒ ***conditions are highly accurate***

Dropping assumptions: detailed converter model

voltage source model:



detailed converter model with LC filter:



- ***idea:*** **invert** LC filter so that $v \approx v_{dc} u$

→ ***control:*** perform robust inversion of LC filter via **cascaded PI**

- ***analysis:*** repeat proof via **singular perturbation Lyapunov** functions

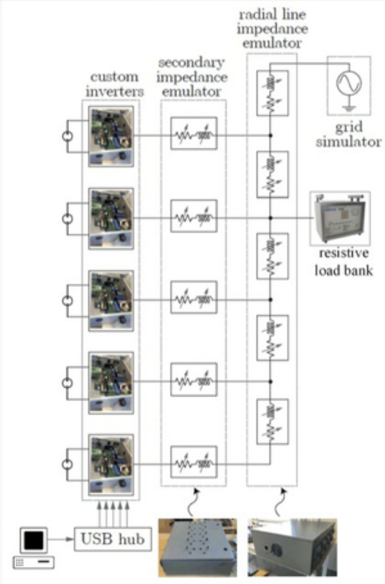
→ ***almost global stability*** for sufficient time scale separation (quantifiable)

VOC model $<$ line dynamics $<$ voltage PI $<$ current PI

[Subotic, ETH Zürich Master thesis '18]

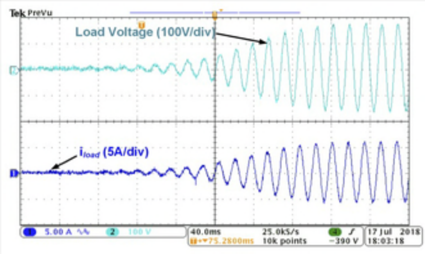
- …similar steps for control of v_{dc} in a more detailed model

Experimental setup @ NREL

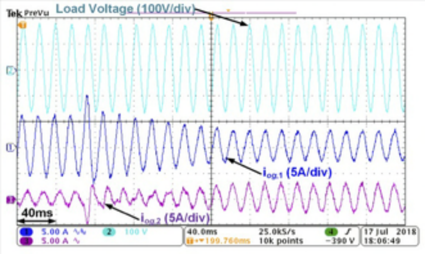


Experimental results

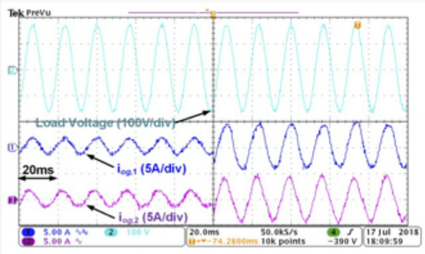
[Seo, Subotic, Johnson, Colombino, Groß, & Dörfler, APEC'18]



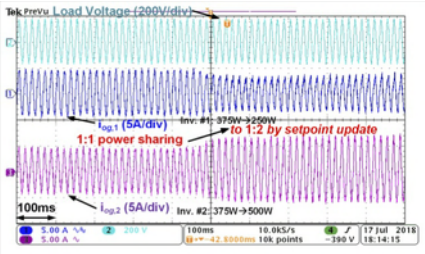
black start of inverter #1 under 500 W load (making use of almost global stability)



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

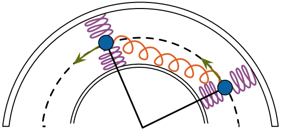


change of setpoint: $p^\star$ of inverter #2 updated from 250 W to 500 W

Conclusions

Summary

- challenges of low-inertia systems
- dispatchable virtual oscillator control
- theoretic analysis & experiments



Ongoing & future work

- theoretical questions: robustness & regulation
- practical issue: compatibility with legacy system
- experimental validations @ ETH, NREL, AIT

Main references (others on website)

D. Groß, M Colombino, J.S. Brouillon, & F. Dörfler. *The effect of transmission-line dynamics on grid-forming dispatchable virtual oscillator control*.

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*.


POWER IS NOTHING WITHOUT CONTROL