ETH zürich

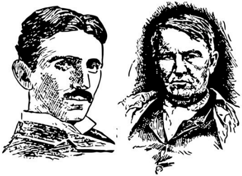
Control in Low-Inertia Power Systems: from the device level to the system level

Florian Dörfler

ETH Zürich

UNIFI Meeting 2022

Replacing the power system foundation



fuel & synchronous machines	*renewables & power electronics*
– **not sustainable**	+ **sustainable**
+ **central & dispatchable** generation & ancillary service provision	– **distributed & variable** generation & ancillary service provision
+ **large** rotational **inertia** as buffer	– almost **no energy storage**
+ **self-synchronize** through the **grid**	– **no** inherent **self-synchronization**
+ **resilient** voltage / frequency **control**	– **fragile** voltage / frequency **control**
– **slow** actuation & **control**	+ **fast / flexible / modular control**

Issues are broadly recognized

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

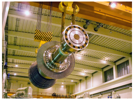
→ led to almost comical situations . . .

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

USING DECOMMISSIONED NUCLEAR POWER PLANT AS SYSTEM SERVICE PROVIDERS

REPORT 2017:348

Energiforsk



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

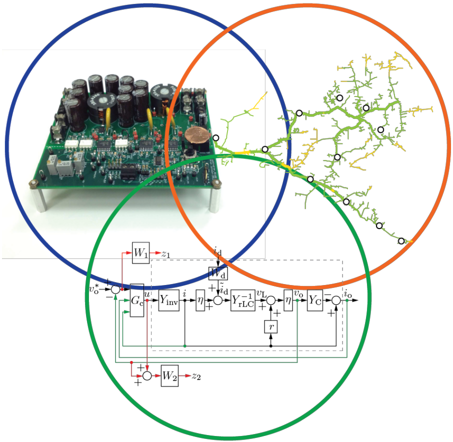
→ industry & academia joining forces & willing to explore **green-field approach**

- since 2015: EU **MIGRATE** project & successors (OSMOSE, POSYTYF, . . .)

- across the pond: unifi consortium

Exciting research bridging communities

power electronics



power systems

control systems

Source: Brian Johnson

theory ↔ practice | device ↔ system | proof ↔ experiment

Outline

Introduction

Device-Level: Grid-Forming Converter Control

System-Level: Ancillary Services in Low-Inertia Grids

Conclusions

Outline

Introduction

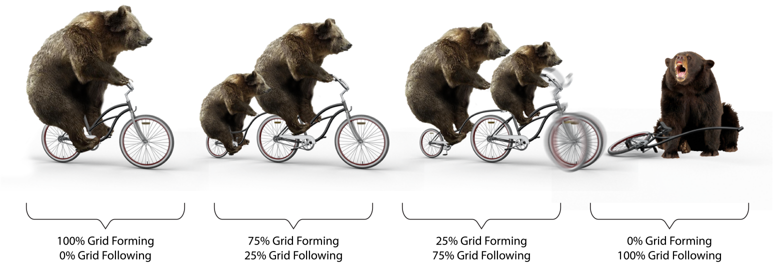
Device-Level: Grid-Forming Converter Control

- Salient Characteristics & Specifications
- State-of-the-Art Grid-Forming Controls
- Synopsis & Lessons Learnt

System-Level: Ancillary Services in Low-Inertia Grids

Conclusions

Grid-forming control

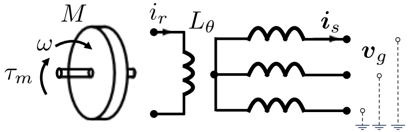


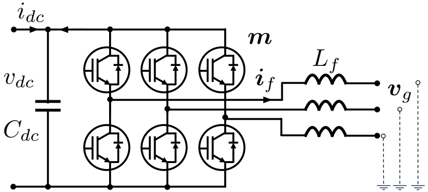
Source: NREL

- fact: power systems need XXX% of **grid-forming sources**
- **no universally accepted definition** of grid-forming behavior

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

Comparison: storage & conversion mechanisms





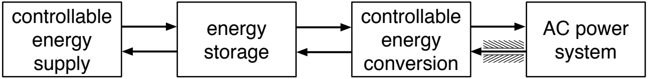
$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = \omega$$

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

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

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

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

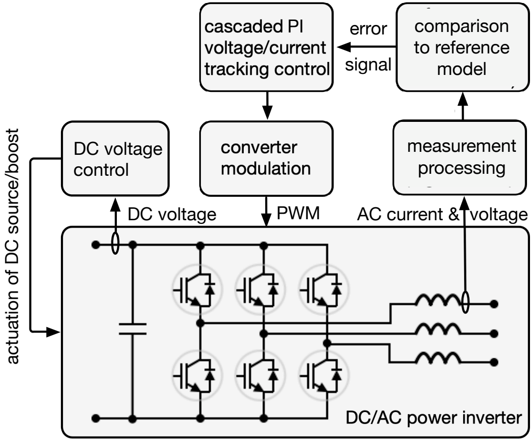


τ_m (slow) vs. i_{dc} (fast)	M (large) vs. C_{dc} (small)	L_θ (physical) vs. $\boldsymbol{m}$ (control)	resilient vs. fragile

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

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

Cartoon of power electronics control



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

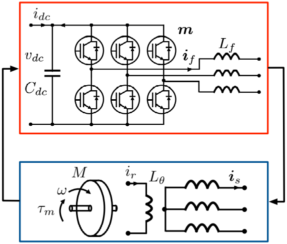
   "how would a synchronous generator respond now ?"
3. cascaded PI controllers to ***track*** reference error

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

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

Conventional reference behaviors

virtual synchronous machine



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

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

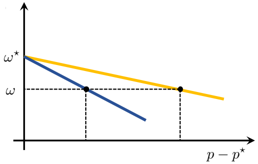
→ **poor fit**: converter ≠ flywheel

  – good small-signal but **poor post-fault performance** (reference not realizable)

  – **over-parametrized** & ignores **limits**

→ ***emulate only "useful" dynamics***

droop / power-synchronization



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

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

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

→ **decoupling ≠ true** in transients

  → **good small-signal but poor large signal** (narrow region of attraction)

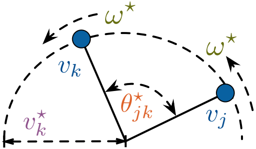
  → main reason: **two linear SISO loops for MIMO nonlinear system**

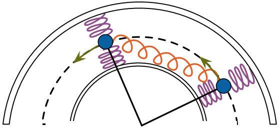
→ ***need "nonlinear & MIMO" droop***

Modern reference behaviors: VOC family

reference model: ***virtual oscillator control (VOC)***

[Aracil, Torres, Johnson, Dhople, Krein, Colombino, Groß, & Dörfler]





- VOC dynamics realizable via **fully decentralized control & set-points**

$$\underbrace{\frac{d}{dt} v_k = \begin{bmatrix} 0 & -\omega^\star \\ \omega^\star & 0 \end{bmatrix} v_k}_{\text{oscillation at } \omega^\star} + c_1 \cdot \underbrace{\left({v_k^\star}^2 - \|v_k\|^2\right) v_k}_{\text{local amplitude regulation}} + c_2 \cdot \underbrace{\left(\frac{1}{{v_k^\star}^2} \begin{bmatrix} q_k^\star & p_k^\star \\ -p_k^\star & q_k^\star \end{bmatrix} v_k - i_{f,k} \right)}_{\text{synchronization through grid current}}$$

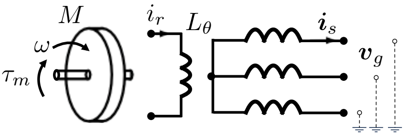
- polar coordinates reveal **nonlinear & multivariable droop control**

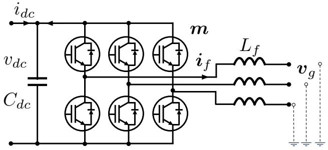
$$\frac{d}{dt}\theta_k = \omega^\star + c_2 \left(\frac{p_k^\star}{{v_k^\star}^2} - \frac{p_k}{\|v_k\|^2} \right) \underset{\|v_k\| \approx 1}{\approx} \omega^\star + c_2 \left(p_k^\star - p_k \right) \quad (p - \omega \text{ droop})$$

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

- **strong certificates** (interconnected stability) & **excellent ac performance**

Duality & matching of synchronous machine conversion





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

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

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

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

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

1. modulation in polar coordinates:

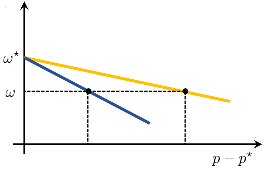
$$\boldsymbol{m} = m_{\mathsf{ampl}} \begin{bmatrix} -\sin\delta \\ \cos\delta \end{bmatrix} \quad \& \quad \dot{\delta} = m_{\mathsf{freq}}$$

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

2. ***matching***: $m_{\mathsf{freq}} = \eta v_{\mathsf{dc}}$ with $\eta = \frac{\omega^\star}{v_{\mathsf{dc}}^\star}$

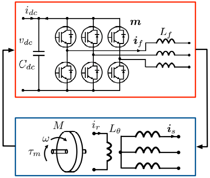
- ***dc frequency***/imbalance signal $\omega \equiv v_{dc}$
- ***dc inertia*** $M \equiv C_{\mathsf{dc}} \equiv$ fast dc source
- **structural** (not quantitative) **similarities**
- **simple & robust** but **slow ac behavior**

High-level comparison of grid-forming control



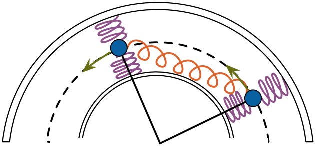
droop control

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



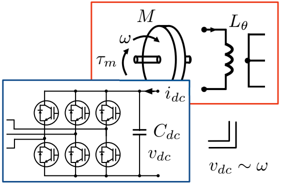
virtual synchronous machine

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



virtual oscillator control

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



matching control & duality

- \+ simple & robust
- – slow ac performance

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

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

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

Comparison of Virtual Oscillator and Droop Control

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Minneapolis, MN 55455
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Similarities between Virtual Oscillator Controlled and Droop Controlled Three-Phase Inverters

Zhan Shi, Hendra I. Nurdin, John E. Fletcher, Jiacheng Li
School of Electrical Engineering and Telecommunications, UNSW Sydney, NSW, 2052, Australia
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Comparative Transient Stability Assessment of Droop and Dispatchable Virtual Oscillator Controlled Grid-Connected Inverters

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

Frequency Stability of Synchronous Machines and Grid-Forming Power Converters

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

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

Ali TAYYEBI
AIT and ETH Zürich – Austria

Florian DÖRFLER
ETH Zürich – Switzerland

Friederich KUPZOG
Austrian Institute of Technology – Austria

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

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

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

Zhan Shi[1], *Jiacheng Li*[1], *Hendra I. Nurdin*[1], *John E. Fletcher*[1]
[1]*School of Electrical Engineering and Telecommunications, UNSW Sydney, UNSW, NSW, 2052, Australia*
E-mail: zhan.shi@unsw.edu.au

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

Grid-Forming Converters control based on DC voltage feedback

Yuan Gao[a], Hai-Peng Ren[a], Jie Li[a]

- identical steady-state & similar small-signal behavior (after tuning)
- virtual synchronous machine has poor transients (converter $\neq$ flywheel)
- **VOC has best large-signal behavior**: stability, post-fault-response, …
- **matching control $\omega \sim v_{\mathrm{dc}}$ is most robust** though with slow AC dynamics
- …comparison suggests ***multivariable control*** (e.g., VOC + matching)

Synopsis & lessons learnt

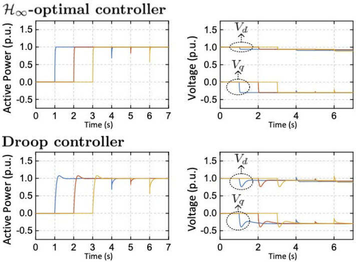
① **converter** $\neq$ **flywheel**: very different actuation & energy storage

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

③ ***multivariable design*** instead of decoupling: simple but results in huge gains

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

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



- blending of VOC + matching controls
- optimal & automated $\mathcal{H}_2$ / $\mathcal{H}_\infty$ design

④ wide open: meet **current constraints** & remain stable post-fault

⑤ synchronization is only the beginning: what to do once sync'd ? **services !**

Outline

Introduction

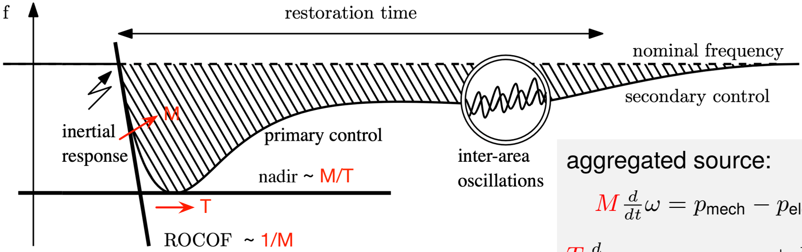
Device-Level: Grid-Forming Converter Control

System-Level: Ancillary Services in Low-Inertia Grids

- System-Level Metrics
- Ancillary Services: Where & How?
- Synopsis & Lessons Learnt

Conclusions

Naive insight: we are loosing inertia



aggregated source:

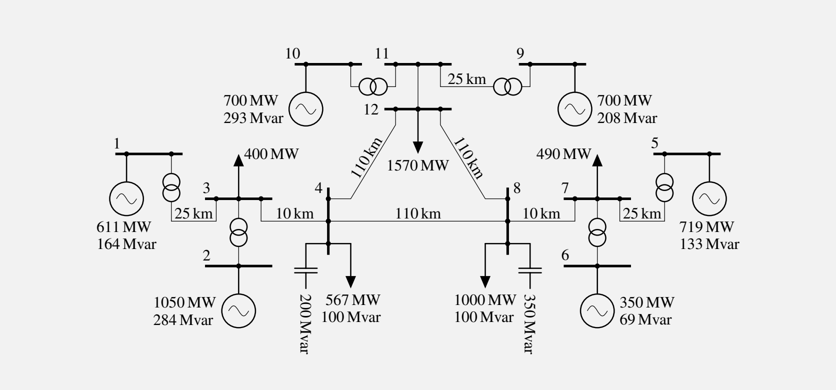
$$M \frac{d}{dt}\omega = p_{\text{mech}} - p_{\text{elec}}$$

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

- **first-order observation**: less inertia $M \implies$ steeper RoCoF & lower nadir
- **second-order observation**: can trade off inertia M with faster actuation T
- **more profound observations**: the above classic hook curves reflect the physical behavior of a system dominated by synchronous machines

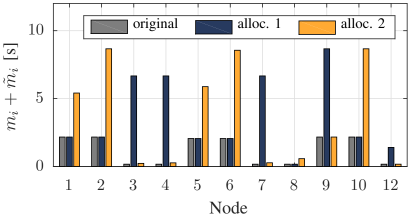
$\rightarrow$ new physical phenomena $\rightarrow$ **new metrics & new ancillary services** needed

Illustrative case study: modified Kundur system

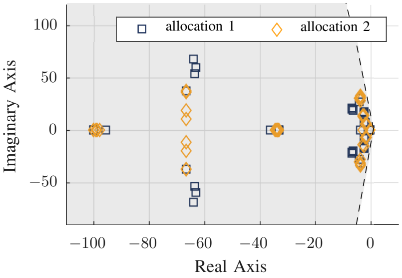


- added 3rd area to standard test case & grid-following virtual inertia at all buses
- original inertia 40s: removed 28s of rotational which can be re-allocated as virtual inertia

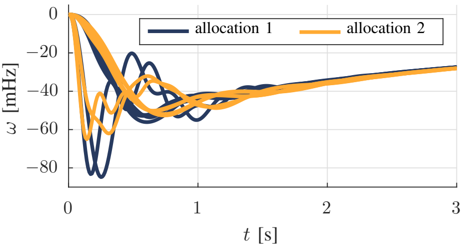
Futile traditional metrics: RoCoF, spectrum, & inertia



metrics	allocation 1	allocation 2
total inertia	40.85 s	40.85 s
damping ratio	0.1190	0.1206
RoCoF	0.8149 Hz/s	0.8135 Hz/s
ω nadir	-84.8 mHz	-65.1 mHz
peak injection	118.38 MW	7.0446 MW
control effort	15.581	2.699



comparison for 100 MW load step at bus 7



More useful metrics: system norms

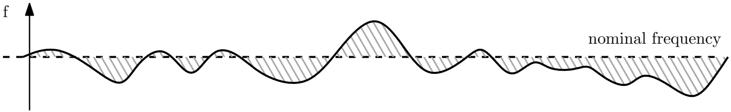
- from step responses in a conventional power system to more modern (1980) **system norms** quantifying the effect of shocks on variables of interest

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

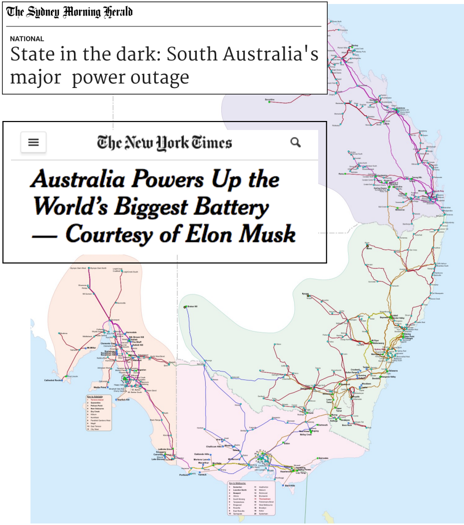
performance outputs: signal energy or peak in time / frequency domain of output

- **versatile setup**: stochastic or deterministic (worst-case) settings
- **practical**: efficiently computable & useful for both analysis & design
- **example:** as a result of fault choose best fast frequency response to minimize

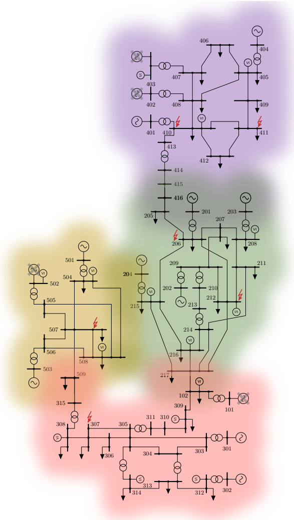
$$\int_0^\infty \{\text{frequency deviation}\}^2 + \{\text{coherency: deviation from COI}\}^2 + \{\text{control effort}\}^2 \, dt$$



Case-study: South-East Australian Grid with B. Poolla & D. Groß

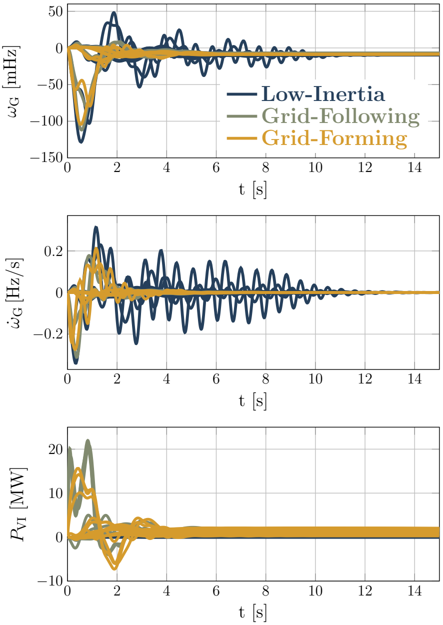


grid topology



simulation model

Closed-loop with optimal fast frequency response



model & fast frequency response

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

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

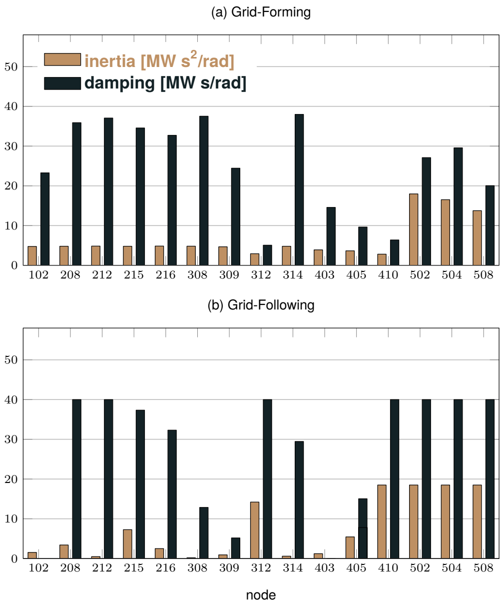
- choose performance inputs / outputs & **optimize response** on linearized model
- nonlinear closed-loop simulations: 200 MW disturbance at node 508

observations

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

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

Optimal allocation of virtual inertia + damping



observations

- both control modes allocate virtual inertia in (blackout & battery) **area 5**
- **grid-following** : more reliance on damping (due to PLL-delay in $\dot{\omega}$)
- **grid-forming** : results in a more uniform (thus robust) allocations

conclusions

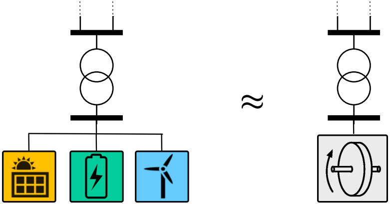
$\rightarrow$ **total inertia/damping** not crucial

$\rightarrow$ in comparison **spatial allocation** & **tuning** make a big difference

$\rightarrow$ implications for pricing & markets

Services from Dynamic Virtual Power Plant (DVPP)

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



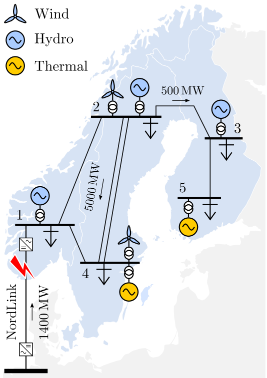
- **heterogenous** collection of devices
  - reliable provide services consistently across all power & energy levels and all time scales
  - none of the devices itself is able to do so
- **dynamic** ancillary services
  - fast response, e.g., inertia for brittle grid, robustly implementable on converter sources
  - specified as desired dynamic I/O response
- **coordination** aspect
  - decentralized control implementation
  - real-time adaptation to variable DVPP generation & ambient grid conditions

examples

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

Nordic case study

with J. Björk (Svenska kraftnät)
& K.H. Johansson (KTH)



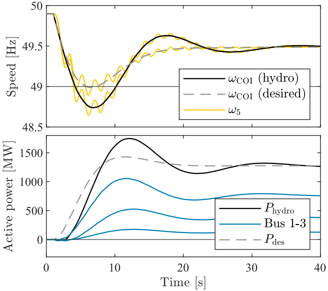
- FCR-D service
  → desired behavior

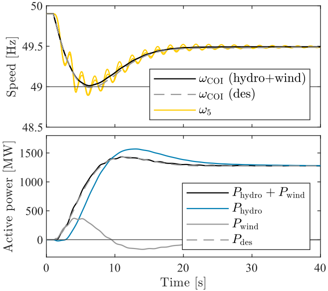
$$\frac{\textit{power}}{\textit{frequency}} = \frac{3100 \cdot (6.5s + 1)}{(2s + 1)(17s + 1)}$$

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

- **discussed solution**: augment hydro with on-site batteries for fast response
  → works but not economic

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





Synopsis & lessons learnt

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

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

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

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

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

Conclusions

- **do not think only of "inertia"** when designing converter controls, analyzing power systems, or specifying ancillary services
- rather: **adopt more system-theoretic & computational mind-set**: specify desired responses & use optimization + multivariable control
- grid-forming control is only part of the puzzle: what to once sync'd? **services!** who provides them? where? how to disaggregate the desired behavior?
- last: **free yourself from textbook plots** – tomorrow's system will be different