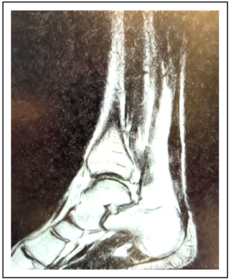
Control in Power-Electronics-Dominated Power Systems

Florian Dörfler

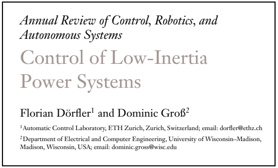
ETH Zürich

Isaac Newton Institute 2023

Acknowledgements & miscellaneous



…partially ruptured Achilles → remote talk



Annual Review of Control, Robotics, and Autonomous Systems

Control of Low-Inertia Power Systems

Florian Dörfler[1] and Dominic Groß[2]

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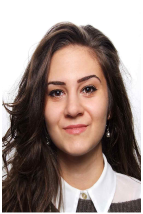
reference for today

Verena Häberle



Irina Subotic

Ali Tayyebi

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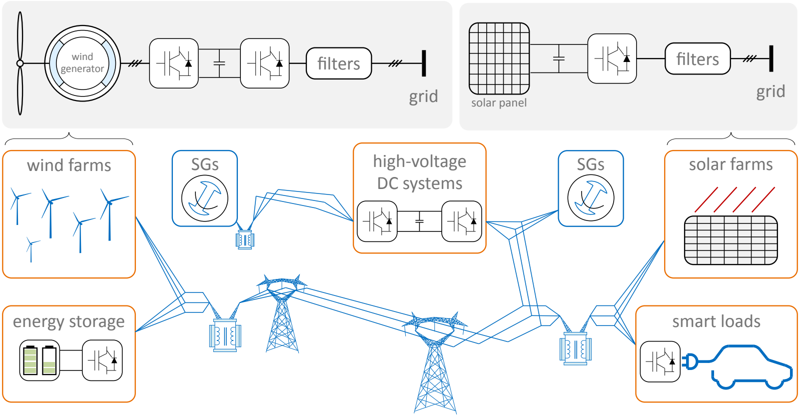
Eduardo Prieto

Catalin Arghir

Meng Chen

Dominic Groß

Power-electronics-dominated power systems



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

Issues are by now broadly recognized

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

→ led to rather comical situations . . .

Biblis A generator stabilizes the grid as a synchronous condenser

USING DECOMMISSIONED NUCLEAR POWER PLANT AS SYSTEM SERVICE PROVIDERS

REPORT 2017:348

Energiforsk

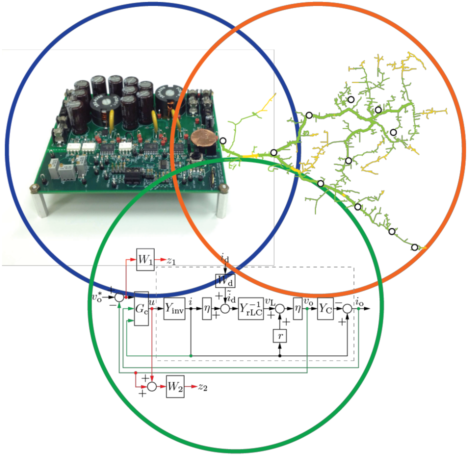
new challenges: low-inertia stability, grid-forming control, & fast frequency support

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

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

- across the pond: unifi consortium

Exciting research bridging communities



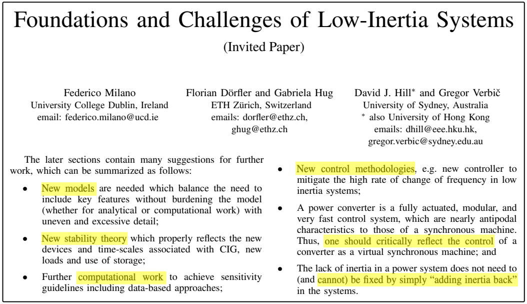
power electronics

power systems

control systems

theory ↔ practice | device ↔ system | proof ↔ experiment

Conclusion: re-visit models / analysis / control / . . .



Foundations and Challenges of Low-Inertia Systems

(Invited Paper)

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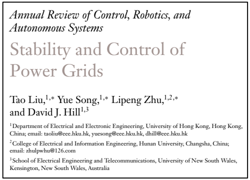
The later sections contain many suggestions for further work, which can be summarized as follows:

- 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.



Annual Review of Control, Robotics, and Autonomous Systems

Stability and Control of Power Grids

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

[1] Department of Electrical and Electronic Engineering, University of Hong Kong, Hong Kong, China; email: taoliu@eee.hku.hk, yuesong@eee.hku.hk, dhill@eee.hku.hk

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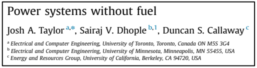
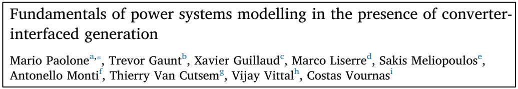
[3] School of Electrical Engineering and Telecommunications, University of New South Wales, Kensington, New South Wales, Australia



Power systems without fuel

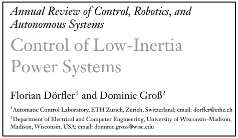
Josh A. Taylor[a,*], Sairaj V. Dhople[b,1], Duncan S. Callaway[c]

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



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

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



Annual Review of Control, Robotics, and Autonomous Systems

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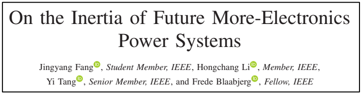
Power system stability in the transition to a low carbon grid: A techno-economic perspective on challenges and opportunities

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



On the Inertia of Future More-Electronics Power Systems

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

focus today : **control** on device & system level

Outline: a *personal* journey through the field

Introduction

Device-Level: Grid-Forming Converter Control

System-Level: Ancillary Services in Low-Inertia Grids

Conclusions

Outline: a *personal* journey through the field

Introduction

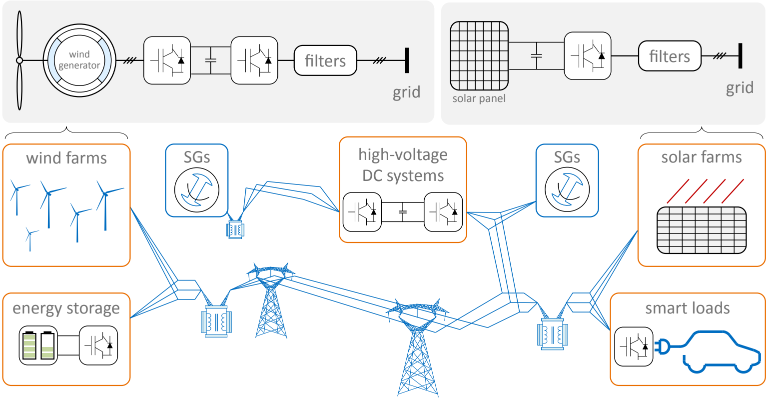
Device-Level: Grid-Forming Converter Control

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

System-Level: Ancillary Services in Low-Inertia Grids

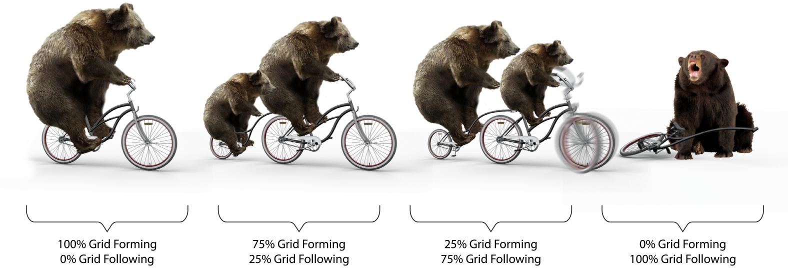
Conclusions

Device-level challenges with inverter-based sources



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

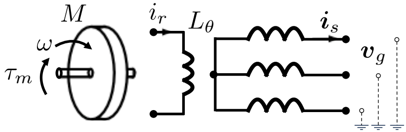
Grid-forming control

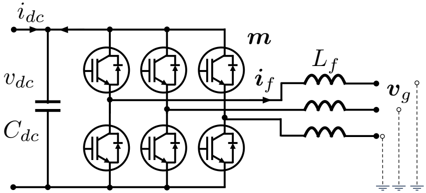


- fact: power systems need XXX% of **grid-forming sources**
- **no universally accepted definition** of grid-forming behavior

	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





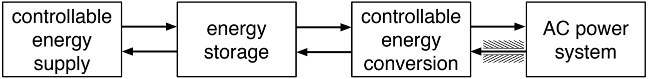
$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = \omega$$

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

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

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

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



controllable energy supply

energy storage

controllable energy conversion

AC power system

τ_m (slow) vs. i_{dc} (fast)

M (large) vs. C_{dc} (small)

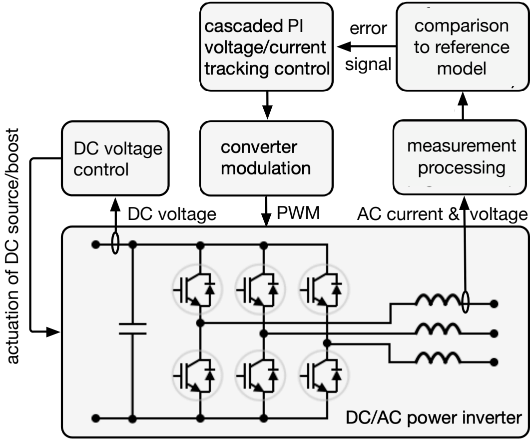
L_θ (physical) vs. $\boldsymbol{m}$ (control)

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)

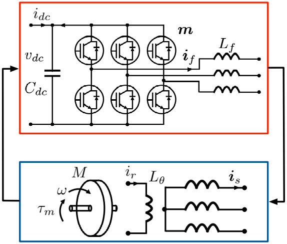
   "how would a synchronous generator respond now ?"
3. cascaded PI controllers to ***track*** reference error

   assumption: no state constraints encountered
4. ***actuation*** via modulation
5. ***energy balancing*** via dc voltage P-control

   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)

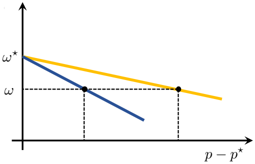
→ most commonly **accepted solution** in **industry** (¿ backward compatibility ?)

→ **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

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

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

→ **decoupling ≠ true** in transients

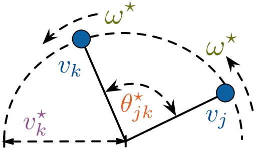
  → **good small-signal but poor large signal** (narrow region of attraction)

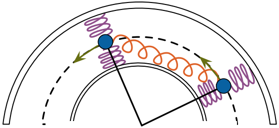
  → main reason: **two linear SISO loops for MIMO nonlinear system**

→ ***need "nonlinear & MIMO" droop***

Modern reference behaviors: VOC family

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





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

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

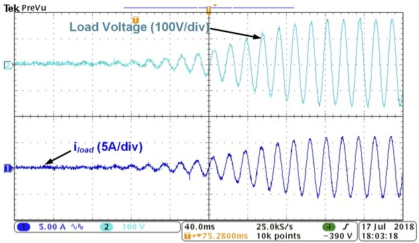
- polar coordinates reveal **nonlinear & multivariable droop control**

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

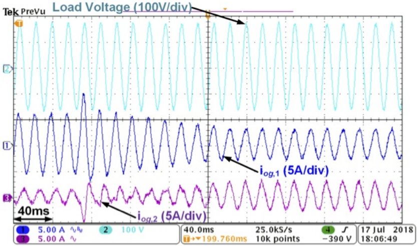
$$\frac{d}{dt}\|v_k\| \underset{\|v_k\| \approx 1}{\approx} c_1 \left(v_k^\star - \|v_k\|\right) + c_2 \left(q_k^\star - q_k\right) \quad (q - \|v\| \text{ droop})$$

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

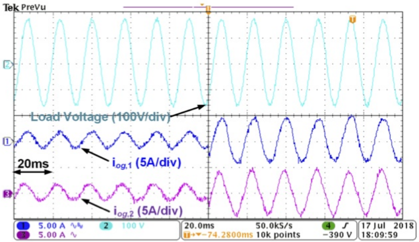
Experimental validation @NREL (often replicated, varied, & extended)



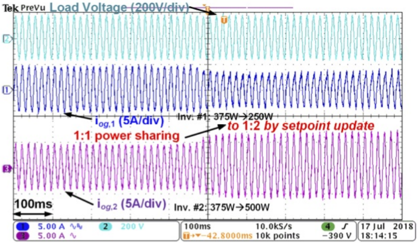
black start of inverter #1 under 500 W load (making use of almost global stability)



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

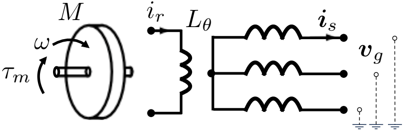


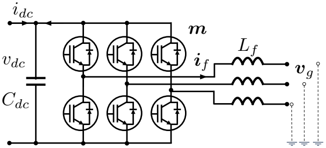
250 W to 750 W load transient with two inverters active



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

Duality & matching of synchronous machine conversion





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

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

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

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

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

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

1. modulation in polar coordinates:

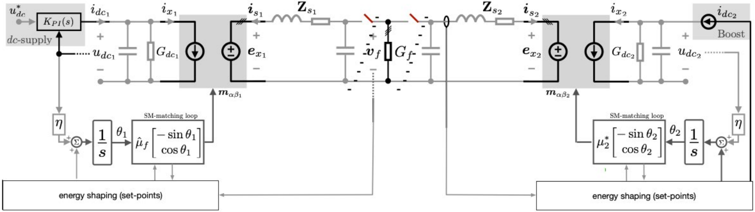
$$\boldsymbol{m} = m_{\mathrm{ampl}} \begin{bmatrix}-\sin\delta\\ \cos\delta\end{bmatrix} \quad \& \quad \dot{\delta} = m_{\mathrm{freq}}$$

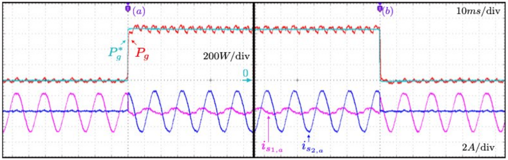
→ ***duality***: $C_{\mathrm{dc}} \sim M$ is equivalent inertia

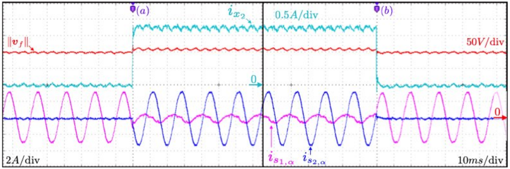
2. ***matching***: $m_{\mathrm{freq}} = \eta v_{\mathrm{dc}}$ with $\eta = \frac{\omega^\star}{v_{\mathrm{dc}}^\star}$

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

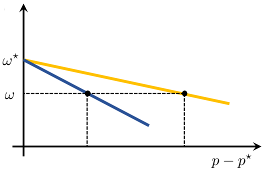
Experimental validation @ETH (concept often replicated with variations)





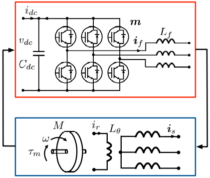


High-level comparison of grid-forming control



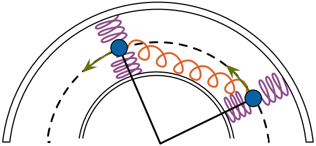
droop control

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



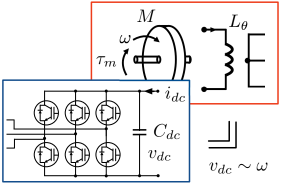
virtual synchronous machine

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



virtual oscillator control

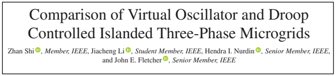
- + excellent large-signal behavior + local droop
- − voc, droop, & vsm need strong dc source



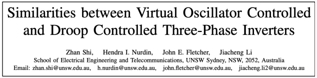
matching control & duality

- + 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*


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

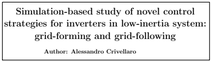
Zhan Shi, Hendra I. Nurdin, John E. Fletcher, Jiacheng Li
School of Electrical Engineering and Telecommunications, UNSW Sydney, NSW, 2052, Australia
Email: zhan.shi@unsw.edu.au, h.nurdin@unsw.edu.au, john.fletcher@unsw.edu.au, jiacheng.li2@unsw.edu.au


Frequency Stability of Synchronous Machines and Grid-Forming Power Converters

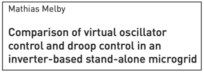
Ali Tayyebi, Dominic Groß, *Member, IEEE*, Adolfo Anta, Friederich Kupzog and Florian Dörfler, *Member, IEEE*


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

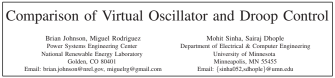
Minghui Lu*, Victor Purba†, Sairaj Dhople†, Brian Johnson*


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


Comparison of Virtual Oscillator and Droop Control

Brian Johnson, Miguel Rodriguez
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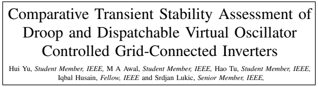
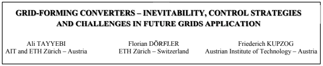

Comparative Transient Stability Assessment of Droop and Dispatchable Virtual Oscillator Controlled Grid-Connected Inverters

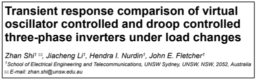
Hui Yu, *Student Member, IEEE,* M A Awal, *Student Member, IEEE,* Hao Tu, *Student Member, IEEE,*
Iqbal Husain, *Fellow, IEEE* and Srdjan Lukic, *Senior Member, IEEE,*


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


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

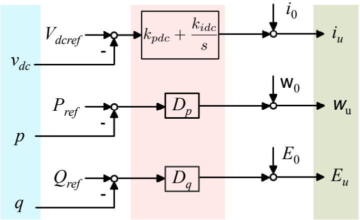

Grid-Forming Converters control based on DC voltage feedback

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

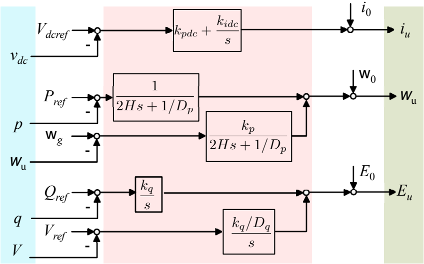
- identical steady-state & similar small-signal behavior (after tuning)
- virtual synchronous machine has poor transients (converter $\neq$ flywheel)
- **VOC has best large-signal behavior** : stability, post-fault-response, …
- **matching control** $\omega \sim v_{\text{dc}}$ **is most robust** though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

Abstract perspective on converter controls

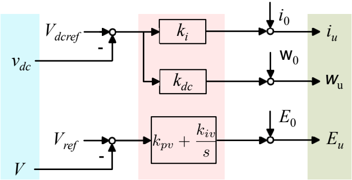
① **droop** control = 3 decoupled **SISO** loops



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



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



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

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

or droop **adapting** to impedance angle φ

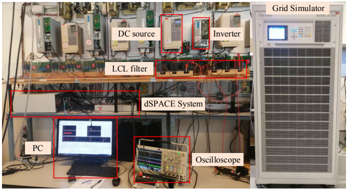
$$\begin{bmatrix} p \\ q \end{bmatrix} \mapsto \begin{bmatrix} \cos\varphi & \sin\varphi \\ -\sin\varphi & \cos\varphi \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \mapsto \text{control loops} \mapsto u$$

⇒ seek ***MIMO, dynamic, & nonlinear*** control

Optimal multivariable grid-forming control

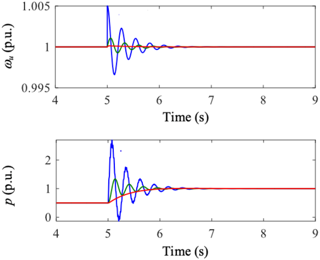
$$\begin{bmatrix} u_1 \\ \vdots \\ u_m \end{bmatrix} = \mathbb{K}(s) \begin{bmatrix} y_1 \\ \vdots \\ y_p \end{bmatrix}$$

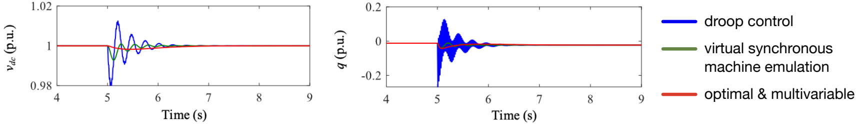
- inputs: modulation, dc-power supply, & inner references
- outputs: (nonlinear) state tracking errors



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

- **optimal/robust linear design** via $\mathcal{H}_2$ / $\mathcal{H}_\infty$ & nonlinear implementation
- **forming / following mode** enforced by small-signal Bode characterization
- **linear stability** under interconnection





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
→ based on optimization & account for grid-forming / following specifications
→ motivates **architecture-free definitions** of grid connection requirements

④ open & hard problem: satisfy **current constraints** & remain stable post-fault

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

Outline: a *personal* journey through the field

Introduction

Device-Level: Grid-Forming Converter Control

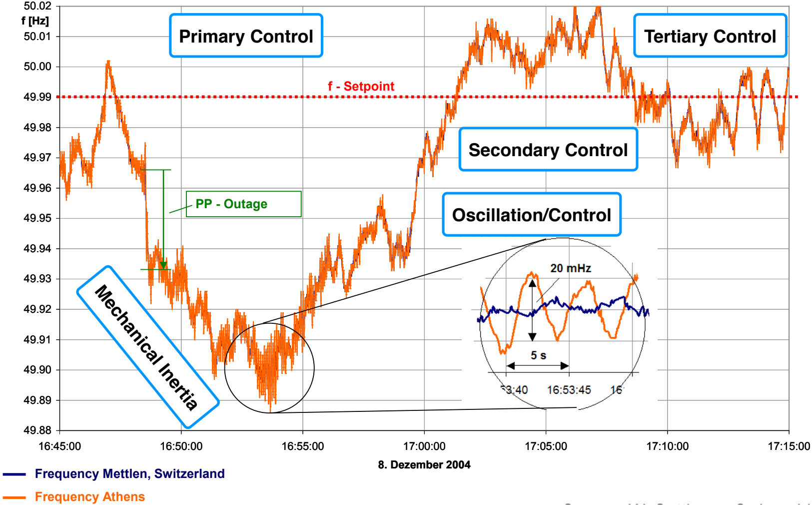
System-Level: Ancillary Services in Low-Inertia Grids

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

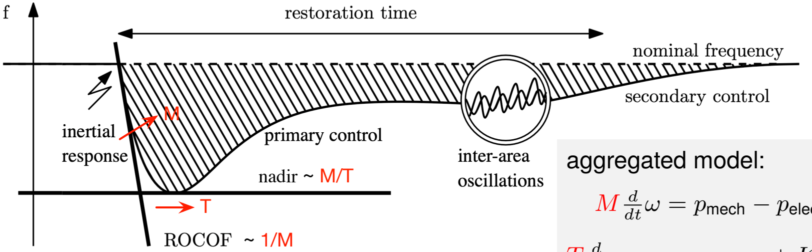
Conclusions

Hook curve & services in conventional system

source: W. Sattinger, Swissgrid



Naive insight: we are loosing inertia



aggregated model:

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

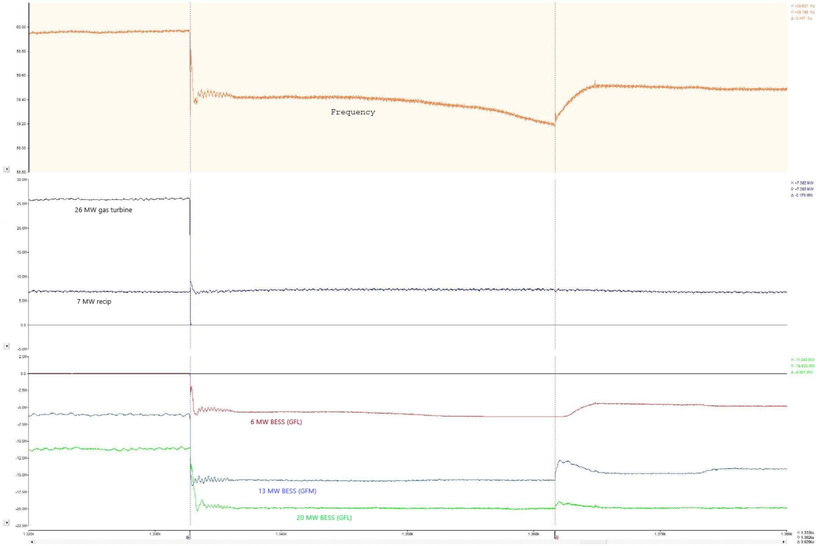
$$T \frac{d}{dt} p_{\text{mech}} = -p_{\text{mech}} + K\omega$$

- **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

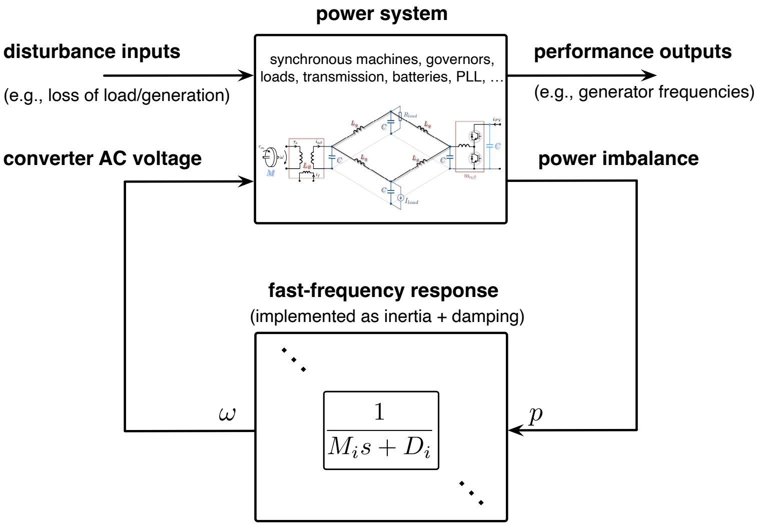
→ new physical phenomena → **new metrics & new ancillary services** needed

Fact: no more hook curves in low-inertia systems

source: confidential – but you can make your guesses



Fast frequency response provided by converters



power system

disturbance inputs

(e.g., loss of load/generation)

synchronous machines, governors, loads, transmission, batteries, PLL, …

performance outputs

(e.g., generator frequencies)

converter AC voltage

power imbalance

fast-frequency response

(implemented as inertia + damping)

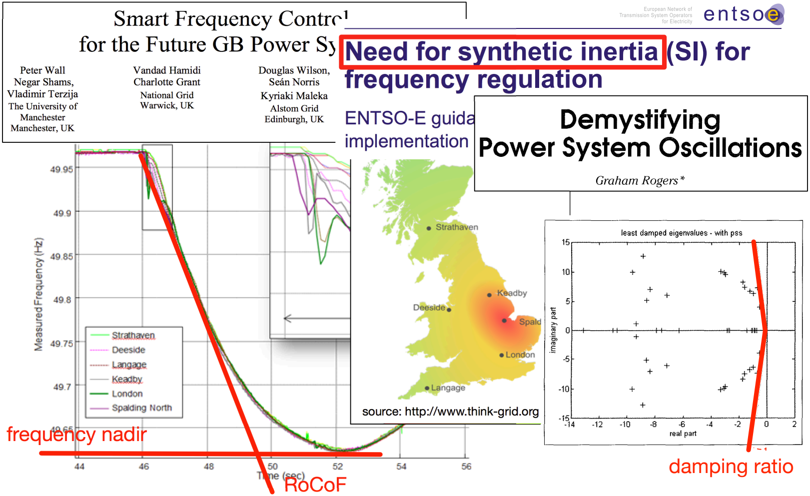
ω

p

$$\frac{1}{M_i s + D_i}$$

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

Historic & revived (but naive !) metrics: damping ratio, RoCoF, nadir, & total inertia



Smart Frequency Contr
for the Future GB Power Sy

Peter Wall
Negar Shams,
Vladimir Terzija
The University of Manchester
Manchester, UK

Vandad Hamidi
Charlotte Grant
National Grid
Warwick, UK

Douglas Wilson,
Seán Norris
Kyriaki Maleka
Alstom Grid
Edinburgh, UK

European Network of Transmission System Operators for Electricity entsoe

Need for synthetic inertia (SI) for frequency regulation

ENTSO-E guida
implementation

source: http://www.think-grid.org

Demystifying Power System Oscillations

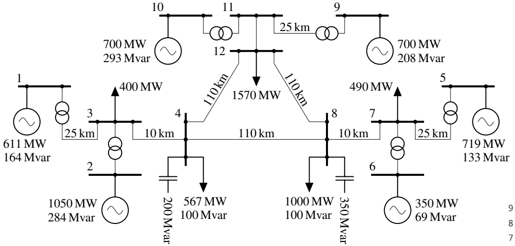
*Graham Rogers**

frequency nadir

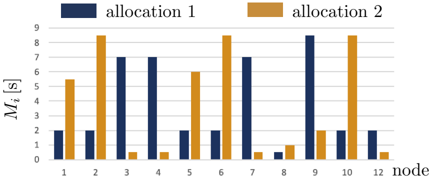
RoCoF

damping ratio

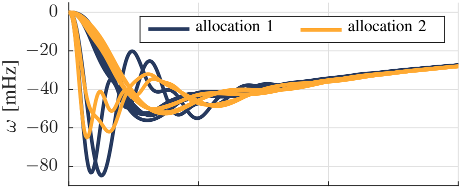
Futility of traditional metrics



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



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 energy	15.581	2.699

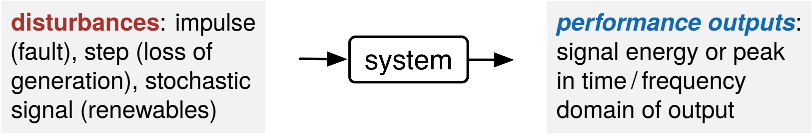


comparison for 100 MW load step at bus 7

traditional metrics ambiguous → **discard**

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



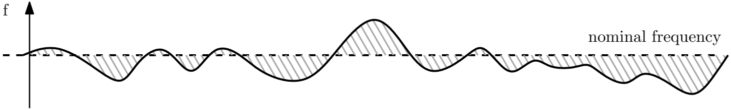
disturbances: impulse (fault), step (loss of generation), stochastic signal (renewables)

system

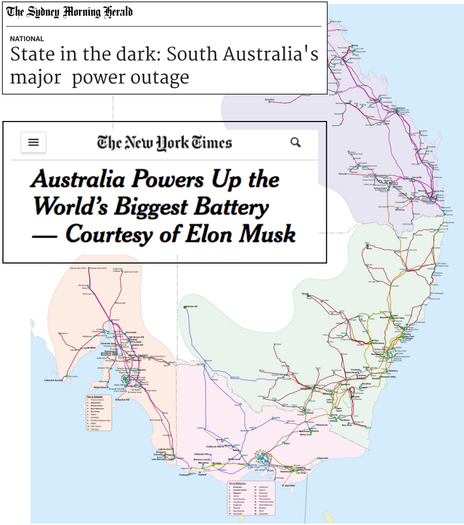
performance outputs: signal energy or peak in time / frequency domain of output

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



The Sydney Morning Herald

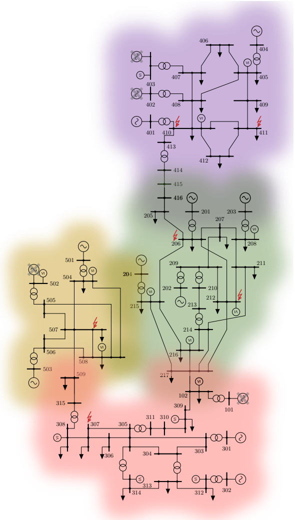
NATIONAL

State in the dark: South Australia's major power outage

The New York Times

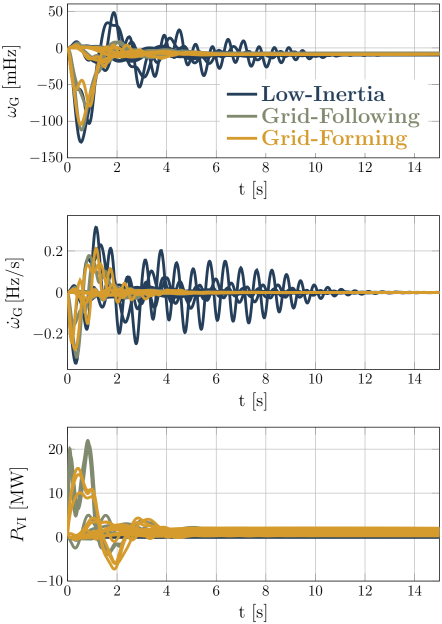
Australia Powers Up the World's Biggest Battery — Courtesy of Elon Musk

grid topology



simulation model

Closed-loop with optimal fast frequency response



model & fast frequency response

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

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

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

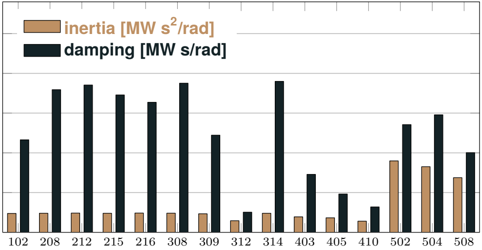
observations

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

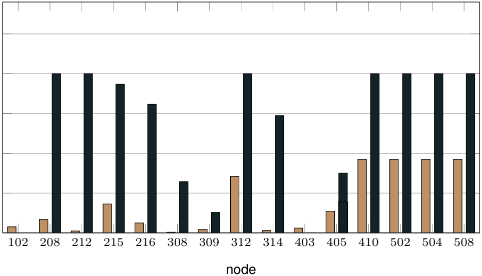
→ **forming beats following** in nadir, RoCoF, & peak power

Optimal allocation of virtual inertia + damping

(a) Grid-Forming



(b) Grid-Following



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

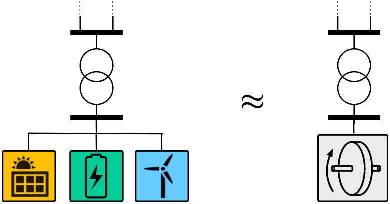
→ **total inertia/damping** not crucial

→ in comparison **spatial allocation** & **tuning** make a big difference

→ implications for pricing & markets

Services from Dynamic Virtual Power Plant (DVPP)

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

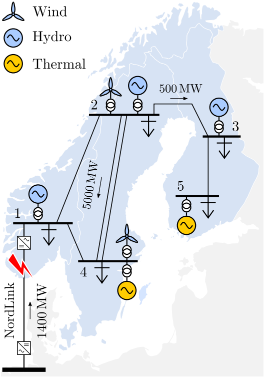


- **heterogenous** collection of devices
  - reliable provide services consistently across all power & energy levels and all time scales
  - none of the devices itself is able to do so
- **dynamic** ancillary services
  - fast response, e.g., inertia for brittle grid, robustly implementable on converter 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



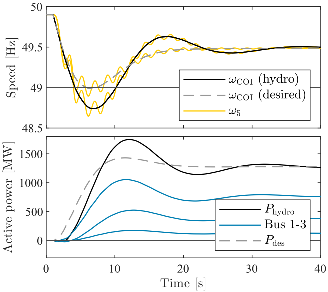
- **FCR-D service**
  → desired behavior

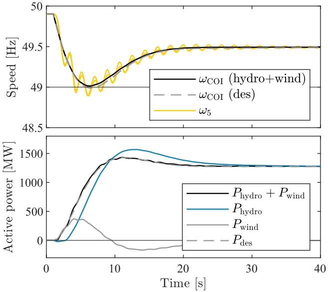
$$\frac{\textit{power}}{\textit{frequency}} = \frac{3100 \cdot (6.5s + 1)}{(2s + 1)(17s + 1)}$$

- 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





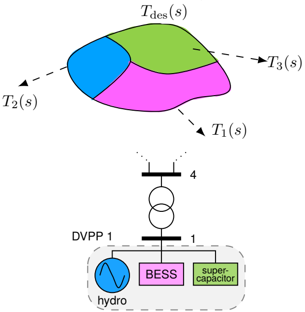
Enabler: dynamic & adaptive participation factors

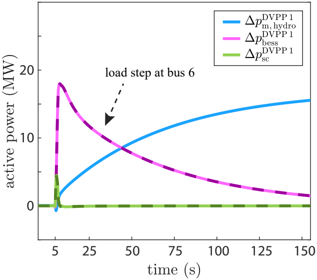
- specify desired **aggregate DVPP behavior** $T_{\text{des}}(s)$, e.g., a desired fast frequency response $p \mapsto f$

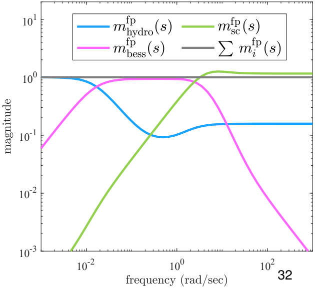
- **disaggregate** $T_{\text{des}}(s)$ into local desired behaviors for each device taking **dynamics constraints** into account & **adapt** disaggregation to varying ambient conditions via **dynamic & adaptive participation factors**

$$T_i(s) = \boldsymbol{m_i(s)}\, T_{\text{des}}(s)$$

- **decentralized model matching** control to achieve $T_i(s)$







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 + **share & location of grid-forming** sources

Preliminary ideas on future ancillary service specs

- **decoupling issues** with standard services separating (p, θ) & $(q, \|v\|)$ dynamics

→ recall VOC error coordinates & define

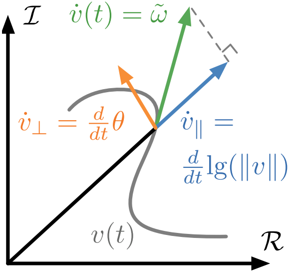
normalized power $\boxed{\tilde{s} = p/\|v\|^2 + \mathrm{i}\, q/\|v\|^2}$

complex frequency $\boxed{\tilde{\omega} = \frac{d}{dt}\mathrm{lg}(\|v\|) + \mathrm{i}\, \frac{d}{dt}\theta}$

[Milano, 2022]

→ VOC $=$ **complex droop**: $\boxed{\tilde{\omega} - \tilde{\omega}^\star \sim \tilde{s} - \tilde{s}^\star}$

→ ***the right coordinates*** for analysis & control !?!



- from **static** to **dynamic ancillary service** specifications, including, e.g., roll-off, PD-action, interconnected stability certificates, forming/following specifications, …

→ ideally seek ***architecture-free & computationally tractable*** definitions, e.g.,

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

Conclusions

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