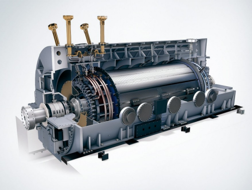
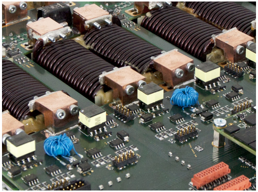
Control and end-to-end stability analysis of converter dominated power systems

Dominic Groß

University of Wisconsin-Madison

We are replacing the foundation of today's grid





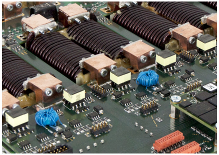
fuel & synchronous machines

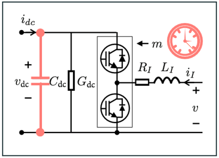
- − **emissions** & **waste**
- \+ **dispatchable** generation
- \+ inherent **self-sync.** & **inertia**
- \+ **reliable** control & **ride-through**
- − **slow** actuation & **physics**

renewables & power electronics

- \+ **clean** & **sustainable**
- − **intermittent** generation
- − no inherent **sync.** or **inertia**
- − **fragile** grid-following **control**
- \+ **fast** actuation & **flexible** control

Overview





The role of inertia & dynamics of converter-interfaced generation (CIG)

- **why** do we need rotational inertia? **how much**?
- **impact** of CIG on **system-level** frequency **dynamics**

Grid-forming and grid-following control

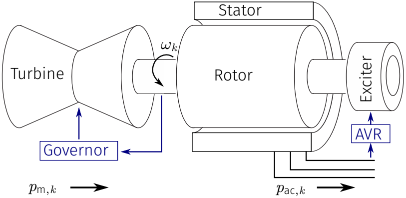
- **principles**, **control strategies**, & results
- a **universal** grid-forming control **paradigm**
- **end-to-end** stability **analysis**: generation, conversion, & network

Opportunities for data-enabled optimization & analysis

- **stability & performance**: reserves, network topology, ...
- validating **interoperability** using **input-output data**

The role of inertia & converter-interfaced generation

The foundation of today's system operation



Sync. machine frequency dynamics

$$m_k \tfrac{\mathrm{d}}{\mathrm{d}t}\omega_k = -d_k\omega_k - p_{\mathrm{ac},k} + p_{\mathrm{m},k}$$

$$\tau_k \tfrac{\mathrm{d}}{\mathrm{d}t}p_{\mathrm{m},k} = -p_{\mathrm{m},k} + p_k^\star - K_k(\omega_0 - \omega_k)$$

1. **self-synchronization** of machines **through power flows**

$$p_{\mathrm{ac},k} \approx \sum\nolimits_j b_{kj}\left(\theta_k - \theta_j\right)$$

2. **inertia** m_k acts as **buffer** for **slow turbine/governor** response
3. **primary frequency control**, voltage regulation, **power system stabilizer**

Low-inertia concerns are not hypothetical (but seem exaggerated?)

MIGRATE project:
Massive InteGRATion of power Electronic devices

INDEPENDENT

News › World › Australasia

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

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

Future Ancillary Services in ERCOT

with a high
system. The

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

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

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

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

ELSEVIER

The relevance of inertia in power systems

Pieter Tielens *, Dirk Van Hertem

Frequency Stability Evaluation Criteria for the Synchronous Zone of Continental Europe

– Requirements and impacting factors –

RG-CE System Protection & Dynamics Sub Group

However, as these sources are fully controllable, a regulation can be added to the inverter to provide "synthetic inertia". This can also be seen as a short term frequency support. On the other hand, these sources might be quite restricted with respect to the available capacity and possible activation time. The inverters have a very low

Biblis A generator stabilizes the grid as a synchronous condenser

amprion

SIEMENS

1004 IEEE JOURNAL OF EMERGING AND SELECTED TOPICS IN POWER ELECTRONICS, VOL. 8, NO. 2, JUNE 2020

Frequency Stability of Synchronous Machine
and Grid-Forming Power Converters

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

IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 34, NO. 4, JULY 2019

Placement and Implementation of Grid-Forming
Grid-Following Virtual Inertia and Fast
Frequency Response

Bala Kameshwar Poolla, *Student Member, IEEE*, Dominic Groß, *Member, IEEE*,
and Florian Dörfler, *Member, IEEE*

REPORT

MIGRATE

Deliverable 3.6: Requirement guidelines for operating a grid with 100% power electronic devices.

Authors: Thibault PREVOST, Guillaume DENIS

Beyond low-inertia systems: Massive integration of grid-forming power converters in transmission grids

A. Crivellaro[1,2], A. Tayyebi[1,3], C. Gavriluta[1], D. Groß[3], A. Anta[1], F. Kupzog[1], and F. Dörfler[3]
[1]AIT Austrian Institute of Technology, Austria [2]University of Padova, Italy [3]ETH Zürich, Switzerland

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

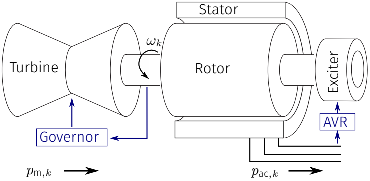
Grid Tied Converter with Virtual Kinetic
Storage

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

Synchronous machines & slow turbine can be replaced by

- **grid-forming** power converters (self-synchronizing, **no PLL**)
- **fast frequency response** & (expensive?) **virtual inertia**

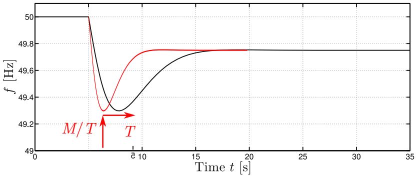
The elephant in the room: loss of SG inertia



“System” frequency dynamics

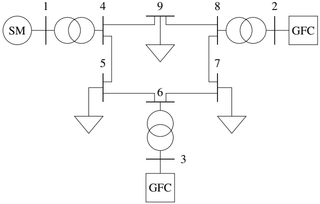
$$\color{darkred}{m/\tau}\,\frac{\mathrm{d}}{\mathrm{d}t'}\omega = -p_{\mathrm{ac}} + p_{\mathrm{m}}$$

$$\frac{\mathrm{d}}{\mathrm{d}t'}p_{\mathrm{m}} = -p_{\mathrm{m}} + p^{\star} - K(\omega_0 - \omega)$$

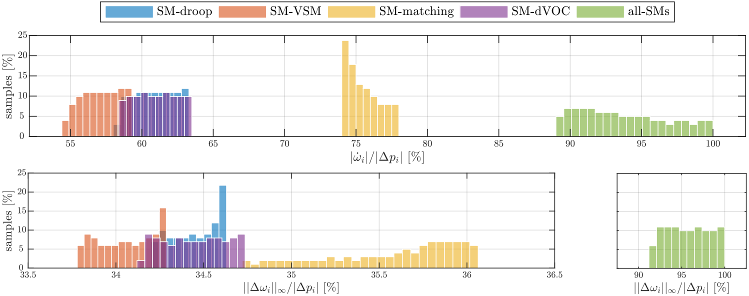


- center-of-inertia (COI) frequency model
- **inertia** m acts as **buffer** for **slow turbine**
- **normalize** time $t' = \tau t$
- **nadir** scales with **ratio** m/τ
- power source time constants
  - battery $\tau \approx 50\ \mathrm{ms}$
  - Wind turbine $\tau \approx 300\ \mathrm{ms}$
  - Steam turbine $\tau \approx 7\ \mathrm{s}$
- Need to leverage **fast** and **flexible** actuation of **IBRs/VSCs**
- **max. RoCoF** approx. linear in m
  - mostly related to m at **machine buses**
  - no rotating parts at **converter bus**
  - RoCoF protection?

IEEE 9-bus with one sync. machine and two grid-forming converters



- high-fidelity simulation:
  - high-order SM with turbine, AVR, & PSS
  - VSC with filter, inner loops, & DC side
  - transformer & line dynamics
- tuning: no or negligible virtual inertia
- better performance than all SM case



Tayyebi, Groß, Anta, Kupzog, Dörfler: *Frequency Stability of Synchronous Machines and Grid-Forming Power Converters*, IEEE JESTPE, 2020

Qualitative analysis of a two-bus system

Simplified frequency dynamics of a two bus system (droop GFC & SM)

- share of GFC relative to overall rating: $\nu \in (0, \frac{2}{3}]$

$$\begin{aligned}
\tfrac{\mathrm{d}}{\mathrm{d}t}\theta_{\mathsf{GFC}} &= (\nu d_{\mathsf{GFC}})^{-1} b(\theta_{\mathsf{SM}} - \theta_{\mathsf{GFC}}) \\
\tfrac{\mathrm{d}}{\mathrm{d}t}\theta_{\mathsf{SM}} &= \omega_{\mathsf{SM}} \\
(1-\nu) m \tfrac{\mathrm{d}}{\mathrm{d}t}\omega_{\mathsf{SM}} &= -b(\theta_{\mathsf{SM}} - \theta_{\mathsf{GFC}}) + p_\tau - p_l \\
\tau \tfrac{\mathrm{d}}{\mathrm{d}t} p_\tau &= -p_\tau - (1-\nu) d_{\mathsf{SM}} \omega
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- m and τ are large → eliminate "fast" angle dynamics (COI model)

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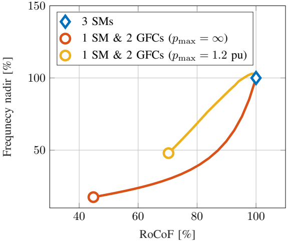

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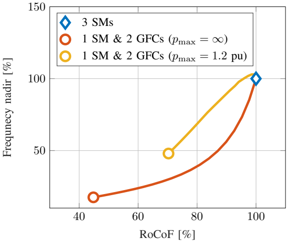


⇒ Fast frequency response replaces slow SM turbine/governor

[1] Tayyebi, Groß, Anta, Kupzog, Dörfler: *Frequency Stability of Synchronous Machines and Grid-Forming Power Converters*, IEEE JESTPE, 2020

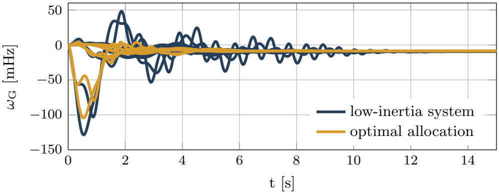
Caveat: inertia placement in weakly coupled systems

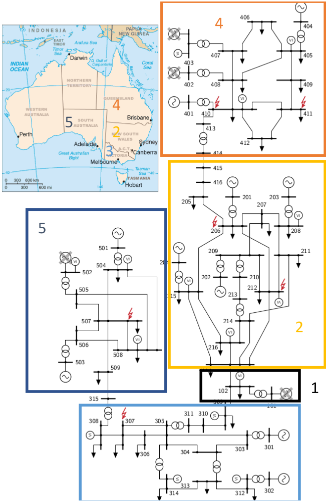
Inertia placement problem

- minimize **disturbance amplification**
- **device-limits** & grid-code **constraints**

Efficient $\mathcal{H}_2$-norm optimization [1]

- **structured** control design problem
- **$\mathcal{H}_2$-norm** optimization (complexity $\mathcal{O}(n^3)$)





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[1] Poolla, Groß, Dörfler: *Placement and Implementation of Grid-Forming and Grid-Following Virtual Inertia and Fast Frequency Response,* IEEE TPWRS, 2019

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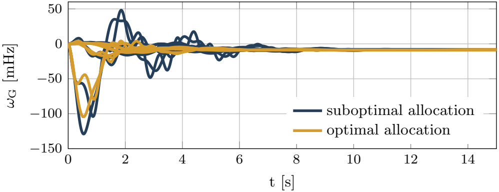

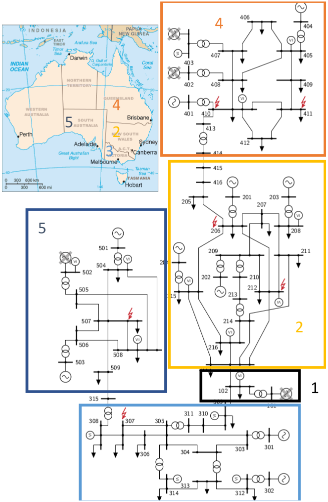

⇒ **location & tuning** matters in large systems with “weak” coupling

[1] Poolla, Groß, Dörfler: *Placement and Implementation of Grid-Forming and Grid-Following Virtual Inertia and Fast Frequency Response,* IEEE TPWRS, 2019

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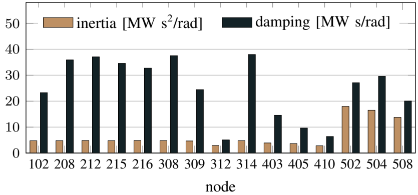
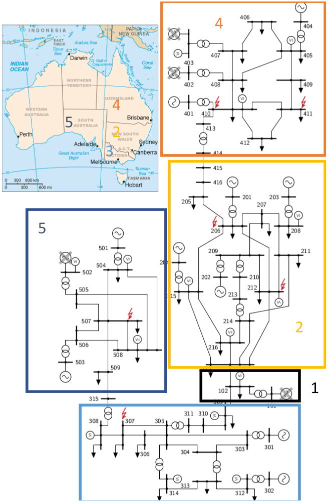




Note: **$\mathcal{H}_2$-norm** optimization requires full system knowledge

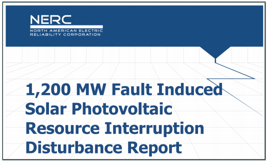
[1] Poolla, Groß, Dörfler: *Placement and Implementation of Grid-Forming and Grid-Following Virtual Inertia and Fast Frequency Response*, IEEE TPWRS, 2019

Grid-forming vs. grid-following control

Actual contingencies involving power electronics

BLACK SYSTEM
SOUTH AUSTRALIA
28 SEPTEMBER 2016

AEMO



NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

1,200 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report

AEMO

Final Report – Queensland and South Australia system separation on 25 August 2018

*“**Nine** of the **13** wind farms online **did not ride through** the six **voltage disturbances** during the event”*

25% of generation lost

*“the **largest** percentage of **inverter loss** (700 MW) was due to the **inverter phase lock loop (PLL)** ”*

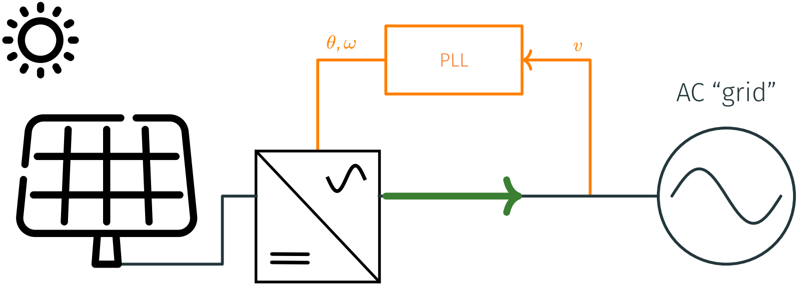
50% of credible cont.

*“The **fast response** of the Hornsdale **battery** during the event **contributed** to operation of the **EAPT scheme**.”*

30% of primary control

- Some controls lack basic robustness / resilience of SGs
- standard time-scale separation assumptions fail
- interoperability with legacy devices not guaranteed

Grid-following (GFL) control: renewables & DC voltage control



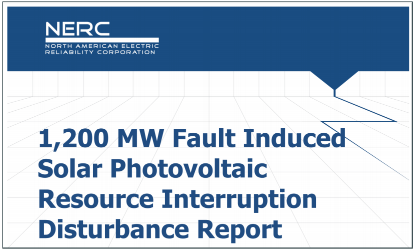
Basic assumptions & objectives

- **assumption:** AC power system is an **infinite AC bus**
- **converter model:** **AC current source** feeding into an **infinite AC bus**
- **objective:** **control** DC voltage (e.g., PV MPPT, HVDC, ...)

More accurately: AC-GFL/DC-GFM control

- DC-GFM: **forms** stable **DC voltage** (not necessarily constant or nominal)
- AC-GFL: **requires** another device to **stabilize** the **AC voltage**

Challenge: PLL-based AC-GFL control is fragile



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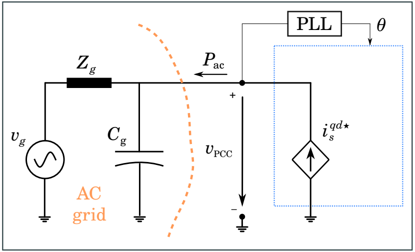


> *"the **largest** percentage of **inverter loss** (700 MW) was due to the **inverter phase lock loop (PLL)** "*

Lack of resilience to line opening, ...

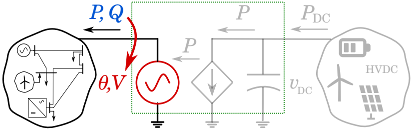
- v_{PCC} depends on IBR current $i_s^{qd\star}$
- PLL can induce positive feedback

Non-trivial dependence of stability on operating point and grid conditions

[1] Dong, Wen, Boroyevich, Mattavelli, Xue: *Analysis of Phase-Locked Loop Low-Frequency Stability in Three-Phase Grid-Connected Power Converters Considering Impedance Interactions*, IEEE TIE, 2015

[2] Pattabiraman, Lasseter, Jahns: *Impact of Phase-Locked Loop Control on the Stability of a High Inverter Penetration Power System*, IEEE PES GM, 2019

Grid-forming (GFM) control: grid stability



Droop control [1]

$$\frac{\mathrm{d}}{\mathrm{d}t}\theta_k = \omega_0 + m_p\left(p_k^\star - p_{\mathrm{ac},k}\right)$$
$$p_{\mathrm{ac},k} \approx \sum_j b_{kj}(\theta_k - \theta_j)$$

Basic assumptions & objectives

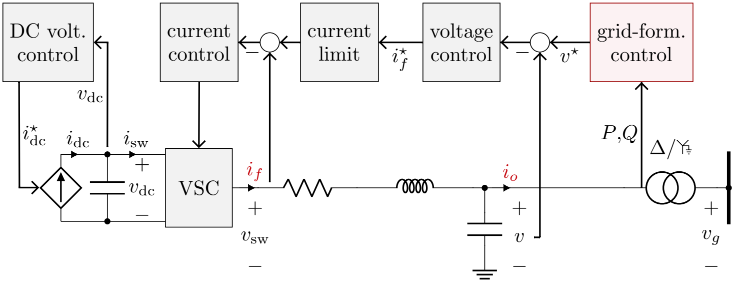
- **assumption:** DC terminal is an infinite DC bus
- **converter model:** AC voltage source feeding network (no current limits)
- **objective:** stabilize AC network at desired operating point

More accurately: AC-GFM/DC-GFL control

- AC-GFM: forms stable AC voltage (not necessarily constant or nominal)
- DC-GFL: requires another device to stabilize the DC voltage

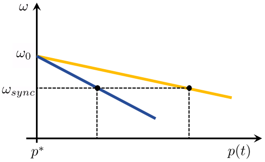
[1] Chandorkar, Divan, Adapa: *Control of Parallel Connected Inverters in Standalone AC Supply Systems*, IEEE TIA, 1993

Standard grid-forming VSC control architecture



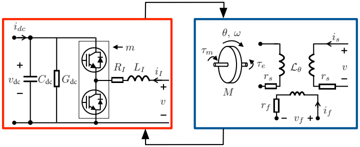
- **Assumption:** DC source controls **DC voltage** to **constant** reference
- **GFC measures power** injection P,Q (or current i_o in $\alpha\beta$-frame)
- **GFC provides AC voltage** reference $\angle v^{\star} = \theta$, $\|v^{\star}\| = V$ (or $v_{\alpha\beta}^{\star}$ in $\alpha\beta$-frame)
- **inner** cascaded **current and voltage PI** controllers track **AC voltage reference**

State-of-the-art in grid-forming control



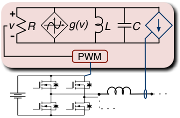
droop control

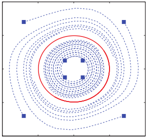
- + intuitive & good small-signal performance
- − stability & performance certificates



synchronous machine emulation

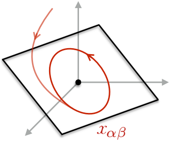
- + (supposedly) backward compatible
- − fast converter emulates slow machine





virtual oscillator control (VOC)

- + robust & almost globally stable sync
- − cannot meet power specifications



dispatchable VOC

- + power & voltage specifications
- + strong theoretical guarantees

dVOC for multi-converter systems

Grid-forming voltage reference dynamics [1]

$$\frac{d}{dt} v_k = \underbrace{\begin{bmatrix} 0 & -\omega_0 \\ \omega_0 & 0 \end{bmatrix} v_k}_{\text{rotation at } \omega_0} + \eta \left(\underbrace{R(\kappa)\Big(\frac{1}{v^{\star 2}} \begin{bmatrix} p_k^\star & q_k^\star \\ -q_k^\star & p_k^\star \end{bmatrix} v_k - i_{o,k}\Big)}_{\text{synchronization through physics}} + \alpha \underbrace{\left(v^{\star 2} - \|v_k\|^2\right) v_k}_{\text{local amplitude regulation}} \right)$$

quantifiable and intuitive stability conditions for multi-converter systems [2]

- $v^\star$, $p_k^\star$, and $q_k^\star$ satisfy **AC power flow equations**
- **power transfer** “small enough” compared to **network “connectivity”**
- increase **admittance** $\max_k \sum_j \| Y_{jk} \|$ × **time-constant** $\ell / r \Rightarrow \eta$ **smaller**
- **upgrading** or **adding** lines can **destabilize** the system
- **time scale separation** can be enforced by control

$$\boxed{\text{magnitude } (\eta\alpha) \; > \; \text{sync } (\eta) \; > \; \text{line currents} \; > \; \text{volt. PI} \; > \; \text{curr. PI}}$$

[1] Groß, Colombino, Brouillon, Dörfler: *The Effect of Transmission-Line Dynamics on Grid-Forming Dispatchable Virtual Oscillator Control*, IEEE TCNS, 2019

[2] Subotić, Groß, Colombino, Dörfler: *A Lyapunov framework for nested dynamical systems on multiple time scales with application to converter-based power systems*, IEEE TAC, 2021

dVOC for multi-converter systems (cont.)

Almost global stability with inner loops & network dynamics (π-model)

If the stability 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.

microgrid ($\ell_{jk} = 0$, $p_k^\star = q_k^\star = 0$) $=$ averaged VOC [Johnson, Dhople, Krein, '13]

$$\frac{\mathrm{d}}{\mathrm{d}t}\theta_k = \omega_0 + \eta \frac{q_k}{\|v_k\|^2} \qquad \text{(phase)}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\|v_k\| = -\eta \frac{p_k}{\|v_k\|^2}\|v_k\| + \eta\alpha\left(\|v_k\| - \frac{1}{v^{\star 2}}\|v_k\|^3\right) \qquad \text{(magnitude)}$$

transmission system ($r_{jk} = 0$, $\|v\| \approx v^\star$) $\approx$ droop control [Chandorkar, Divan, Adapa, '93]

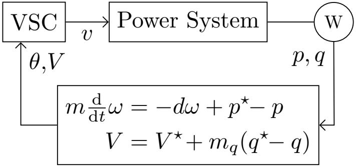
$$\frac{\mathrm{d}}{\mathrm{d}t}\theta_k \approx \omega_0 + \frac{\eta}{v^{\star 2}}\left(p_k^\star - p_k\right) \qquad \text{(phase)}$$

$$\|v_k\| \approx v^\star + \frac{1}{\alpha v^\star}\left(q_k^\star - q_k\right) \qquad \text{(magnitude)}$$

[1] Colombino, Groß, Dörfler: *Global phase and voltage synchronization for power inverters: A decentralized consensus-inspired approach*, CDC, 2017

[2] Seo et al.: *Dispatchable Virtual Oscillator Control for Decentralized Inverter-dominated Power Systems: Analysis and Experiments*, APEC, 2019

Grid-forming controls exhibit similar performance (for realistic tuning)



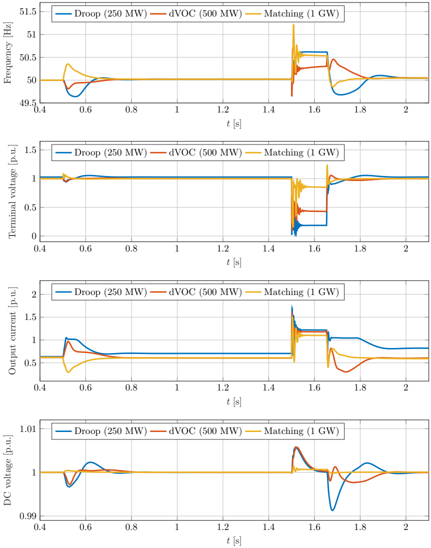
$$m\frac{\mathrm{d}}{\mathrm{d}t}\omega = -d\omega + p^{\star} - p$$
$$V = V^{\star} + m_q(q^{\star} - q)$$

Grid-forming: $(P, Q) \to (\omega, V)$

- sync. through $p \approx \sum_j b_{kj}(\theta_k - \theta_j)$
- virtual inertia m limited by
  - DC side energy storage
  - DC and AC current limits

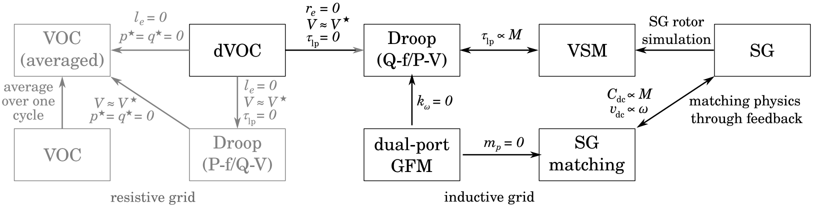
$\to$ m typically **very small**

- **similar** reduced-order **models**
- main GFC response **interoperable**



[1] MIGRATE Deliverable 3.3: *New options for existing system services and needs for new system services*, 2018

Classification & implications of different ac-GFM controls



[1] Dörfler, Groß: *Control of Low-Inertia Power Systems*, submitted.
`http://people.ee.ethz.ch/~floriand/docs/Drafts/2022_ARSurvey.pdf`

Challenges and results in GFM control

Well understood & analytic certificates available

- networks of 100% GFM inverters (with “infinite” DC bus) [1,2,3,...]
- time-scale separation with network dynamics & inner loops [2,3]

Some progress on modeling & analytic certificates

- adverse interactions with machine controls [3,4]
- stability conditions for heterogeneous systems [5]

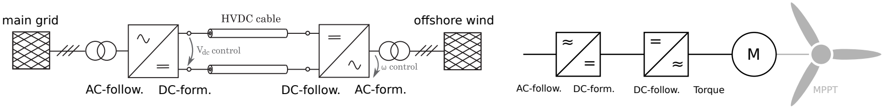
Not well understood

- GFM control subject to converter and power source constraints [6]
- end-to-end stability certificates with dc side & source dynamics [7]
- data-enabled design, optimization, & data-based verification

[6] Tayyebi, Groß, Anta, Kupzog, Dörfler: *Frequency Stability of Synchronous Machines and Grid-Forming Power Converters*, IEEE JESTPE, 2020

[7] Subotić, Groß: *Power-balancing dual-port grid-forming power converter control for renewable integration and hybrid AC/DC power systems*, IEEE TCNS, 2022

Challenge: mixing AC-GFM/DC-GFL and DC-GFM/AC-GFL controls



Definitions for this talk

- AC-GFM (resp. DC-GFM): **imposes** stable AC (resp. DC) **voltage**
- AC-GFL (resp. DC-GFL): **requires** stable AC (resp. DC) **voltage**

GFM/GFL role assignments

- are non-trivial in meshed DC/AC networks [1]
- may have to change during operation
  - MPPT vs. grid-support
  - weather, day/night cycle, season, ...

Numerical results on stability of benchmark systems

- non-trivial dependence on assignment and dispatch
- many assignments only stable for a limited set of operating points
- no assignments covers all operating points in HVAC/HVDC system

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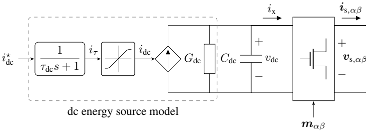
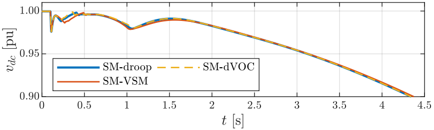
[1] O. Gomis-Bellmunt, E. Sánchez-Sánchez, J. Arévalo-Soler, E. Prieto-Araujo: Principles of operation of grids of DC and AC subgrids interconnected by power converters, *IEEE TPWRD*, 2020

Challenge 3: AC-GFM under converter and source limits





DC terminal not an infinite bus

- power source with limited headroom [1]
- loss of DC-GFM units or DC open-circuit faults [2]

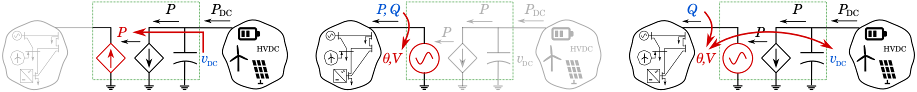
Fault ride through and converter current limits

- low voltage ride through & short-circuit faults [3]
- loss of AC-GFM units or AC open-circuit faults [2]

[1] Tayyebi, Groß, Anta, Kupzog, Dörfler: *Frequency Stability of Synchronous Machines and Grid-Forming Power Converters*, IEEE JESTPE, 2020
[2] Groß, Sánchez-Sánchez, Prieto-Araujo, Gomis-Bellmunt: *Dual-port grid-forming control of MMCs and its applications to grids of grids*, arXiv:2106.11378
[3] MIGRATE Deliverable 3.3: *New options for existing system services and needs for new system services*, 2018

Universal GFM control paradigm

Power sources vs. converters



Power source

- generates power
- **response time** often non-negligible
- limits on power generation

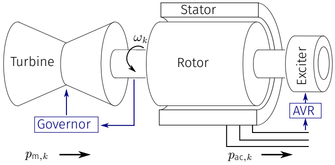
DC/AC voltage source converter

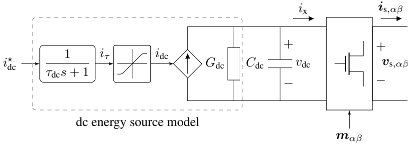
- **converts** power between terminals
- very **small** energy **buffer**
- **current** & voltage **constraints**

DC/AC power balance is crucial to translate between networks and sources

- **AC-GFM/DC-GFL**: stiff DC voltage → form stable AC voltage
- **AC-GFL/DC-GFM**: stiff AC voltage → form stable DC voltage
- **AC-GFM/DC-GFM**: unified control & bidirectional support?

Sync. machine vs. DC/AC converter: power & energy balancing





- rotating mass as energy buffer:

$$\omega(t) \approx \frac{1}{M}\int p_m(t) - p_{\mathrm{ac}}(t)$$

- turbine/governor: $\omega \downarrow$ implies $p_{\mathrm{m}} \uparrow$
- No turbine or no governor:
  - inertia response
  - voltage support

- dc-link capacitor as energy buffer:

$$v_{\mathrm{dc}}(t) \approx \frac{1}{C_{\mathrm{dc}} v^{\star}_{\mathrm{dc}}}\int p_{\mathrm{dc}}(t) - p_{\mathrm{ac}}(t)$$

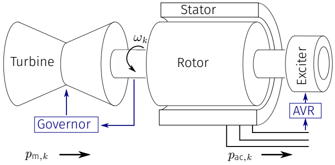
- responsive src.: $v_{\mathrm{dc}} \downarrow$ implies $p_{\mathrm{dc}} \uparrow$

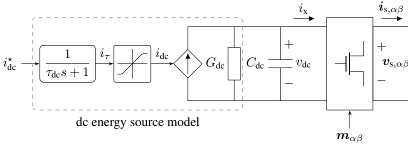
Dual-port GFM control [1]

$$\frac{\mathrm{d}}{\mathrm{d}t}\theta = \omega_0 + m_p(p^{\star}_{\mathrm{ac}} - p_{\mathrm{ac}}) + m_{\mathrm{dc}}(v_{\mathrm{dc}} - v^{\star}_{\mathrm{dc}})$$

[1] Subotić, Groß: *Power-balancing dual-port grid-forming power converter control for renewable integration and hybrid AC/DC power systems*, IEEE TCNS, 2022

Sync. machine vs. DC/AC converter: power & energy balancing





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- no source or source at MPPT:
  - frequency oscillation damping
  - volt-var control

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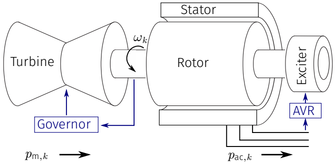

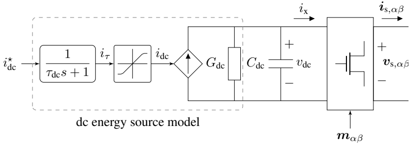

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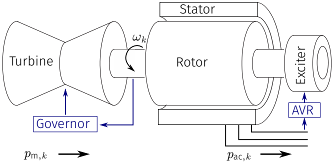

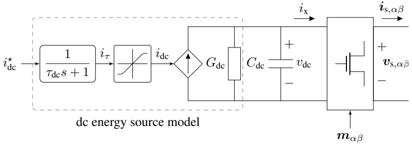

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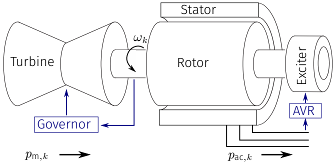
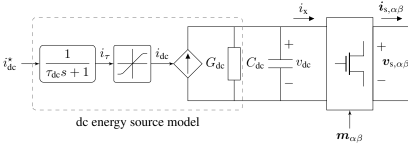
Energy-balancing dual-port GFM control

$$\frac{\mathrm{d}}{\mathrm{d}t}\theta = \omega_0 + m_p(p_{\mathrm{dc}} - p_{\mathrm{ac}}) + m_{\mathrm{dc}}(v_{\mathrm{dc}} - v_{\mathrm{dc}}^{\star})$$

Sync. machine vs. DC/AC converter: power & energy balancing





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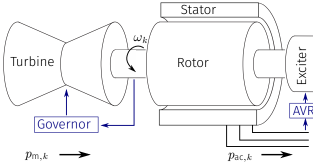
- no source or source at MPPT:
  - frequency oscillation damping
  - volt-var control

Energy-balancing dual-port GFM control

$$\frac{\mathrm{d}}{\mathrm{d}t}\theta = \omega_0 + m_p(p_{\mathrm{dc}} - p_{\mathrm{ac}} - p_{\mathrm{loss}}) + m_{\mathrm{dc}}(v_{\mathrm{dc}} - v_{\mathrm{dc}}^{\star})$$

Sync. machine vs. DC/AC converter: power & energy balancing



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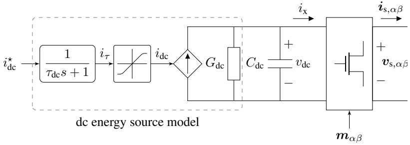

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- no source or source at MPPT:
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  - volt-var control

Energy-balancing dual-port GFM control [2, 3]

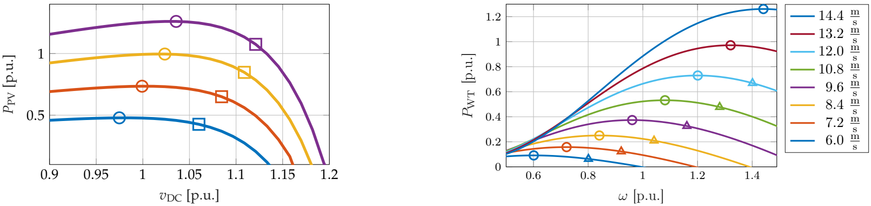
$$\frac{\mathrm{d}}{\mathrm{d}t}\theta = \omega_0 + m_p \frac{\mathrm{d}}{\mathrm{d}t} v_{\mathrm{dc}} + m_{\mathrm{dc}}(v_{\mathrm{dc}} - v_{\mathrm{dc}}^{\star})$$

[2] Groß, Sánchez-Sánchez, Prieto-Araujo, Gomis-Bellmunt: *Dual-port grid-forming control of MMCs and its applications to grids of grids*, IEEE TPWRD, 2022
[3] Lyu, Subotić, Groß: *Unified Grid-Forming Control of Wind Turbines*, IREP, 2022

Dual-port GFM as universal control paradigm for CIG?

Key features:

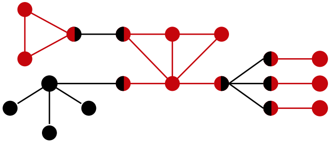
- provides range of “GFL” and “GFM” functions without switching
- Renewable source at MPP → approx. MPPT control [1, 2]
- Renewable source below MPP → “GFM” grid-support [1, 2]
- improved interoperability & unified small-signal stability analysis [1]



[1] Subotić, Groß: *Power-balancing dual-port grid-forming power converter control for renewable integration and hybrid AC/DC power systems*, IEEE TCNS, 2022

[2] Lyu, Subotić, Groß: *Unified Grid-Forming Control of Wind Turbines*, IREP, 2022

End-to-end linear stability analysis for dual-port GFM control



- AC nodes and edges (red)
- DC nodes and edges (black)
- converter nodes (red/black)

Network model and node dynamics (extremely crude)

network power flow

$$P_{\mathsf{ac}} = L_{\mathsf{ac}}\theta, \quad P_{\mathsf{dc}} = L_{\mathsf{dc}}v$$

synchronous machines

$$\tfrac{\mathrm{d}}{\mathrm{d}t}\theta_k = \omega_k$$

$$M_k \tfrac{\mathrm{d}}{\mathrm{d}t}\omega_i = -D_k\omega_k + P_k - P_{\mathsf{ac},k}$$

mechanical power source

$$T_{\mathrm{g},k}\tfrac{\mathrm{d}}{\mathrm{d}t}P_k = -P_k - k_{\mathrm{g},k}\omega_k$$

DC nodes

$$C_k \tfrac{\mathrm{d}}{\mathrm{d}t} v_k = -G_k v_k + P_k - P_{\mathsf{dc},k}$$

DC/AC converter

$$\tfrac{\mathrm{d}}{\mathrm{d}t}\theta_k = -m_{p,k}\tfrac{\mathrm{d}}{\mathrm{d}t}v_k + k_{\theta,k}v_k$$

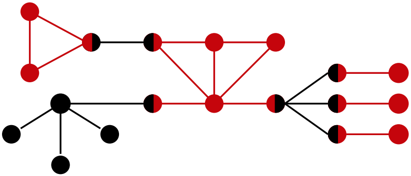
$$C_k \tfrac{\mathrm{d}}{\mathrm{d}t} v_k = -G_k v_k + P_k - P_{\mathsf{ac},k} - P_{\mathsf{dc},k}$$

DC power source

$$T_{\mathrm{g},k}\tfrac{\mathrm{d}}{\mathrm{d}t}P_k = -P_k - k_{\mathrm{g},k}v_k$$

Can model wide range of devices: sync. machines & turbine/governor, sync. condensers, PV, HVDC, wind-turbines, flywheel energy storage, . . .

Basic notation & assumptions



Network & node partitioning

- nodes in i-th AC network: $\mathcal{N}_{\mathsf{ac}}^{i}$ and $\mathcal{N}_{\mathsf{ac/dc}}^{i}$
- nodes in i-th DC network: $\mathcal{N}_{\mathsf{dc}}^{i}$ and $\mathcal{N}_{\mathsf{dc/ac}}^{i}$
- machine and DC/AC nodes with $k_{\mathsf{g},k} > 0$: $\mathcal{N}_{\mathsf{ac^d}}^{i}$ and $\mathcal{N}_{\mathsf{ac/dc^d}}^{i}$
- machine nodes with $k_{\mathsf{g},k} = 0$: $\mathcal{N}_{\mathsf{ac^o}}^{i}$

Assumption 1

- the overall graph of the DC & AC power network is connected
- there exists at least one node with $k_{\mathsf{g},k} > 0$
- $k_{\theta,k} = k_{\theta,l} := k_{\theta}^{i}$ holds for all $i \in \mathbb{N}_{[1,N_{\mathsf{dc}}]}$ and $(k,l) \in \mathcal{N}_{\mathsf{dc/ac}}^{i} \times \mathcal{N}_{\mathsf{dc/ac}}^{i}$

Stability condition

Definitions

- Machine-dominated ($|\mathcal{N}^i_{\text{ac/dc}}| < |\mathcal{N}^i_{\text{ac}}|$): $\mathcal{C}^i := \mathcal{N}^i_{\text{ac}^\text{d}} \cup \mathcal{N}^i_{\text{ac/dc}^\text{d}}$, $\mathcal{D}^i := \mathcal{N}^i_{\text{ac}^\text{o}}$
- Converter-dominated ($|\mathcal{N}^i_{\text{ac/dc}}| \geq |\mathcal{N}^i_{\text{ac}}|$): $\mathcal{C}^i := \mathcal{N}^i_{\text{ac/dc}}$, $\mathcal{D}^i := \mathcal{N}^i_{\text{ac}}$
- “reduced” AC graph $\bar{\mathcal{G}}^i_0$ with node set $\bar{\mathcal{N}}^i_0 := \mathcal{N}^i_{\text{ac}} \cup \mathcal{N}^i_{\text{ac/dc}}$, and edge set $\bar{\mathcal{E}}^i_0 := \mathcal{E}^i_{\text{ac}} \setminus ((\mathcal{D}^i \times \mathcal{D}^i) \cup (\mathcal{C}^i \times \mathcal{C}^i))$
- single-edge node: a node with only one edge

Condition 1 (can be checked independently for every AC network)

One of the following holds for the graph $\bar{\mathcal{G}}^i_0$:

- every node in $\mathcal{D}^i$ is connected to at least one single edge node from $\mathcal{C}^i$
- every node in $\mathcal{D}^i$ is part of a cycle with at least one node from $\mathcal{D}^i$ connected to a single edge node in $\mathcal{C}^i$

Extensions

- $N - x$ stability conditions, steady-state analysis, ...

High-level interpretation

Machine-dominated system

- "enough" sources that respond to imbalances
- "enough" connections from synchronous condensers to sources that respond to imbalances

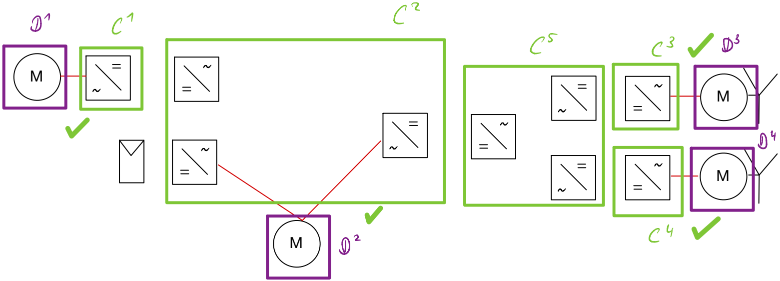
Converter-dominated system

- "enough" connections from synchronous machines to converters
- source that responds to imbalances anywhere in the system

DC networks

- restrictions on control gains
- no conditions on topology

Example: PV, offshore wind, flywheel, sync. condenser, ...



Steps to verify the stability condition

- we only need to look at AC networks in isolation
- split nodes into sets $\mathcal{C}^i$ and $\mathcal{D}^i$
- construct graph $\bar{\mathcal{G}}_0^i$ by only keeping edges between $\mathcal{C}^i$ and $\mathcal{D}^i$

Main result

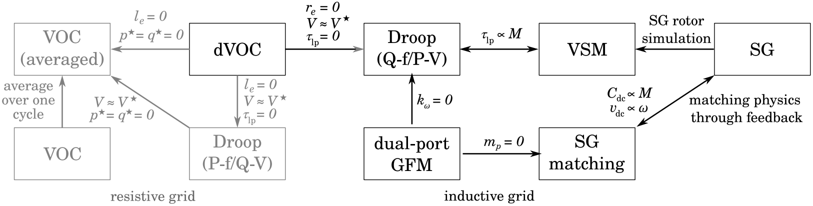
Theorem

If Assumption 1 and Condition 1 hold, then the system is asymptotically stable with respect to $\omega = \mathbb{0}_{|\mathcal{N}_{\text{ac}}|}$, $v = \mathbb{0}_{|\mathcal{N}_{\text{dc}}|+|\mathcal{N}_{\text{ac/dc}}|}$, $P = \mathbb{0}_{|\mathcal{N}_{\text{g}}|}$ and $\theta_j^i = \theta_l^i$ for all $i \in \mathbb{N}_{[1,N_{\text{ac}}]}$.

Discussion

- proof via LaSalle's invariance principle & rank condition on blocks of L_{ac}
- only depends on AC network topology / does not use (exact) line or node parameters
- seems to cover most practically relevant cases (?)
- Topology independent results cannot be established:
  - counter example: one SM with damping & two SMs without damping
  - For any set of network parameters there exist machine parameters such that the system is not asymptotically stable (and vice-versa)

Classification & implications of different ac-GFM controls (revisited)



[1] Dörfler, Groß: *Control of Low-Inertia Power Systems*, submitted.
`http://people.ee.ethz.ch/~floriand/docs/Drafts/2022_ARSurvey.pdf`

Take home messages dual-port GFM control

Universal GFM control paradigm:

- supports standard “GFL” and “GFM” functions without switching controls
- level of grid-support depends on power source (not converter)
  - renewable source at MPP → resilient “GFL” control (no PLL)
  - renewable source below MPP → “GFM” grid-support

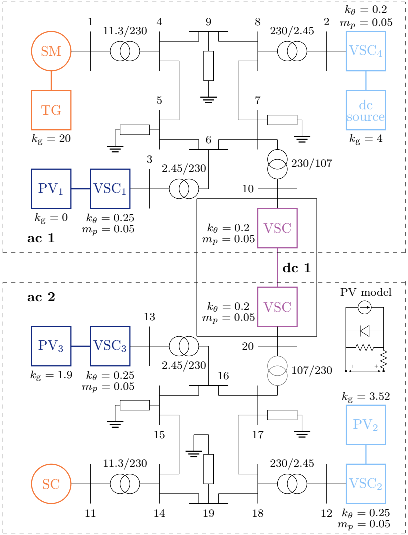
Universal small-signal analysis framework

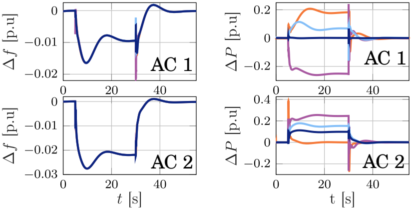
- unified reduced-order modeling framework for wide range of devices
- conditions for frequency stability using partial network knowledge

Open questions

- more detailed network and device models?
- proprietary converter & control implementations?
- (unknown) time-varying topology & CIG flexibility (i.e., $\mathcal{C}^i$, $\mathcal{D}^i$)?

Example: renewable integration & hybrid DC/AC systems using two-level VSCs

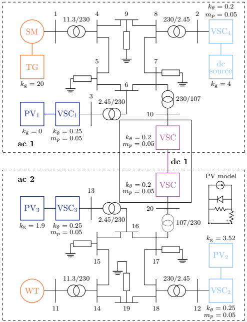


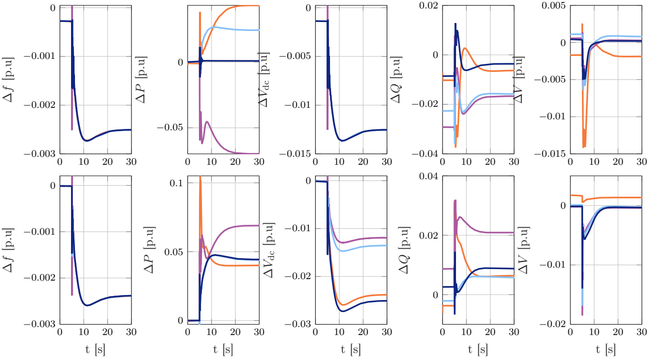


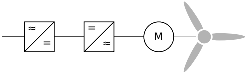
- requires at least **four** "standard" controls
- **"universal" control** on all VSCs
- supports entire spectrum from **MPPT** to **"full" GFM** mode
- grid-support through HVDC
- PV$_1$ at MPP: provides oscillation damping and volt-var support

[1] Subotić, Groß: *Power-balancing dual-port grid-forming power converter control for renewable integration and hybrid AC/DC power systems*, arXiv:2106.10396

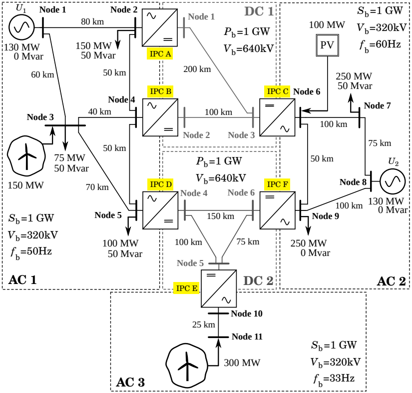
Example: renewables & hybrid DC/AC systems using two-level VSCs

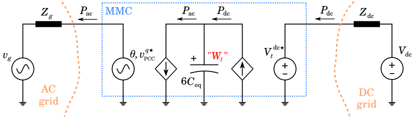






Example: Modular Multilevel Converter (MMC) and hybrid AC/DC systems





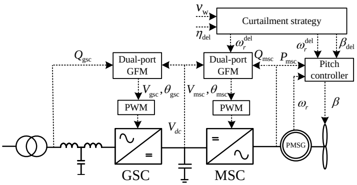
- MMC energy-balancing control

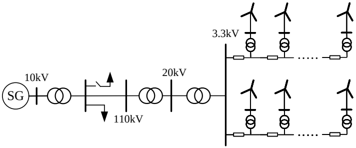
$$\omega = \omega_0 + G_{\text{PD}}(s)(W_t - W_t^\star)$$
$$V_t^{\text{dc}} = V_t^{\text{dc}\star} + G_{\text{PD}}(s)(W_t - W_t^\star)$$

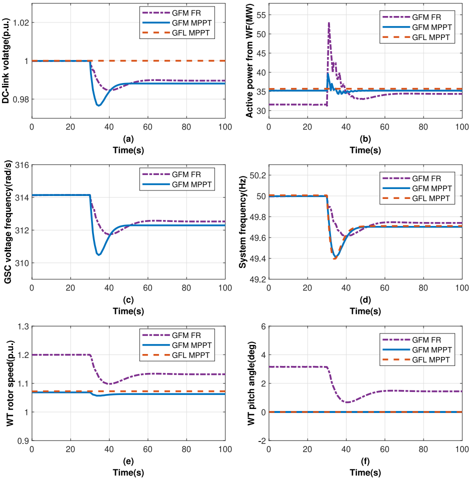
- typically least **three** standard controls
- **“universal” control** on all MMCs
- resilient to **open-circuit faults** & **loss** of AC-GFM and DC-GFM units
- **fully dispatchable** despite lack of power setpoints in MMC control

[1] Groß, Sánchez-Sánchez, Prieto-Araujo, Gomis-Bellmunt: *Dual-port grid-forming control of MMCs and its applications to grids of grids*, arXiv:2106.11378

Example: PMSG Wind turbine







Simulation results at $v_W = 10\ \mathrm{m/s}$

Opportunities for data-enabled optimization & analysis

Opportunities for using data

Crucial assumptions so far

- every converter is using the same control
- partial network knowledge for stability certificates
- full network knowledge for optimization of weakly coupled systems
- only small changes to network and devices (e.g., $N-1$)

vs. reality ...

- limited network knowledge & lots of legacy devices
- proprietary converter hardware & control implementations
- rapid changes in CIG flexibility & role (predictable & unpredictable)
- stability does not imply performance

Validation of vendor-proprietary CIG

SG dynamics “straightforward” to validate

- SG dynamics mostly governed by physics
- same reduced order model for SGs from different vendors
- parameters mostly proportional to rating

CIG as a highly complex blackbox

- no visibility into internals and controls
- identify & learn CIG dynamics from terminal “behaviour”
- compare to known good behaviour? bounds to certify stability?

Data-enabled stability certificates

Stability & performance depend on

- flexibility & reserves of individual sources
- connections between groups of devices (e.g., SCs & MPPT PV to GFM and SGs)

Can we use data to certify stability of stochastic systems

- use day-ahead forecast & statistical analysis to guarantee that enough devices with flexibility & reserves are online [1]
- identify critical connections online?
- abstract “learned” models of legacy devices and protection?

[1] Konstantinopoulos, Avramiotis-Falireas, Bolognani, Groß, Chacko, Hug: Reliability assessment of PV units in primary and secondary frequency control ancillary services, EEM, 2019

Optimization, parameter tuning, & performance

Tuning & placement problems

- heavily depend on dynamics of legacy devices & network topology
- dynamics behind PCC may not be known to operator
- changes to grid topology & devices that are online pose challenges
- increasingly complex interconnections (e.g., HVDC)
- numerical optimization and simulation become intractable

Opportunities for using data

- identify bottlenecks and “weak” areas from data?
- automatically place GFM converters
- responsive decision making based on data-driven optimization?

Take home messages & open problems

Loss of rotational inertia (& slow turbines)

- can be **mitigated** by **fast response** of **grid-forming** converters
- 100% GFC system is **least problematic** (from frequency stability standpoint)
- interoperability of SGs, ac-GFL, ac-GFM not well understood

Universal GFM control paradigm:

- supports MPPT and “GFM” functions (no control switching)
- level of grid-support depends on power source (not converter)
- end-to-end linear stability certificates for many devices & topologies
- impact of dynamics on different time scales?

Outlook

- **stability & performance**: reserves, network topology, …
- validating **interoperability** using **input-output data**