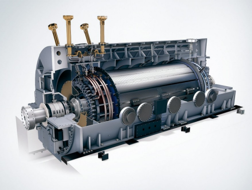
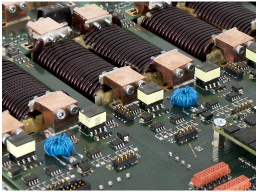
# Beyond low-inertia systems: grid-forming converter control for converter-dominated power systems

Dominic Groß
University of Wisconsin-Madison

PSERC Webinar
March 30, 2021

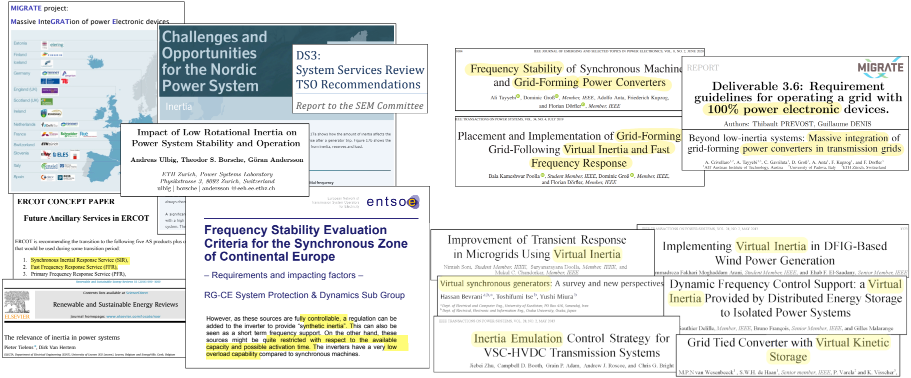
# We are replacing the foundation of today's grid





| fuel & synchronous machines | renewables & power electronics |
| --- | --- |
| − emissions & waste | + clean & cheap |
| + dispatchable generation | − intermittent generation |
| + self-synchronization & inertia | − no inherent sync. or inertia |
| + reliable fault ride-through | − fragile or no fault ride-through |
| − slow actuation & physics | + fast actuation & flexible control |

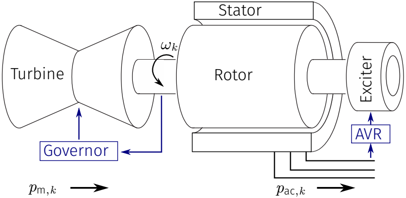
# Low-inertia concerns are not hypothetical (but seem exaggerated?)




## Synchronous machine inertia & slow turbine can be replaced by

- **grid-forming** power converters & curtailed **renewables** or **storage**
- **fast frequency response** & **virtual inertia** (expensive?)


[1] Poolla, Groß, Dörfler: *Placement and Implementation of Grid-Forming and Grid-Following Virtual Inertia and Fast Frequency Response*, IEEE TPWRS, 2019
[2] Tayyebi, Groß, Anta, Kupzog, Dörfler: *Frequency Stability of Synchronous Machines and Grid-Forming Power Converters*, IEEE JESTPE, 2020




**Sync. machine frequency dynamics**

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

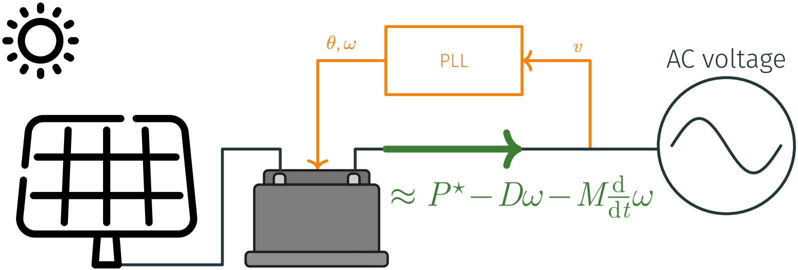
$$\tau_k \frac{\mathrm{d}}{\mathrm{d}t} p_{\mathrm{m},k} = -p_{\mathrm{m},k} + p_k^\star - K_k(\omega_0 - \omega_k)$$

1. system-level model: **voltage source** behind stator reactance
2. **self-synchronization** of machines **through power flows**

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

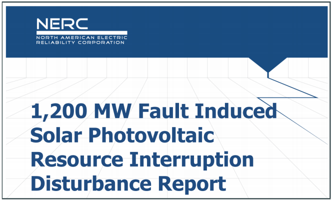
3. **inertia** $m_k$ acts as **buffer** for **slow turbine/governor** response
4. **primary frequency control**, voltage regulation, **power system stabilizer**

# Today: grid-following converter control




- model: **current source** feeding into an **infinite AC bus**
- objective: **stabilize** power **source** at **maximum power point**
- primary **frequency control** & **virtual inertia** (subject to **PLL delay**)

# Actual contingencies involving power electronics


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

25% of generation lost

2016: <40% renewable

2020: <85%, med. 55%

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

50% of credible cont.

Aug. 2016: 4.5 GW solar

Nov. 2020: 10 GW solar

**ERCOT** instantaneous wind & PV: <58%, median 38%

**Ireland** goal for 2030: $<$ 95%, average 70%

# Cartoon summary of grid-forming control

Conceptually, converters can act as AC voltage sources that have to synchronize

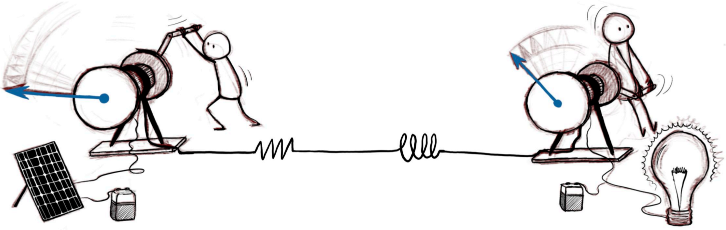


image credit: O. Supponen & M. Colombino

# Cartoon summary of grid-forming control

GFC: converter synchronization through power flows

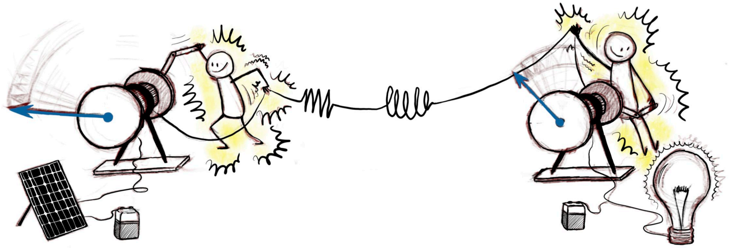
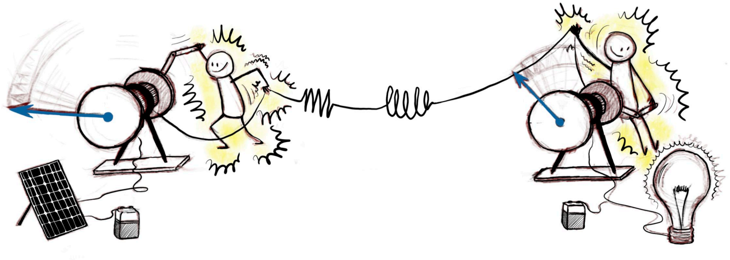
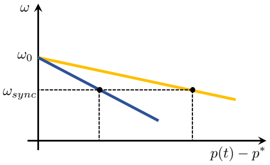


image credit: O. Supponen & M. Colombino

**GFC:** converter **synchronization** through **power flows**



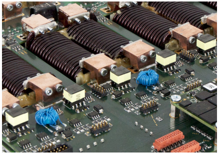


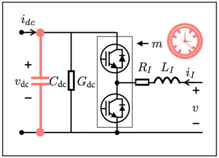

**Droop control** [Chandorkar, Divan, Adapa, '93]

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

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

image credit: O. Supponen & M. Colombino



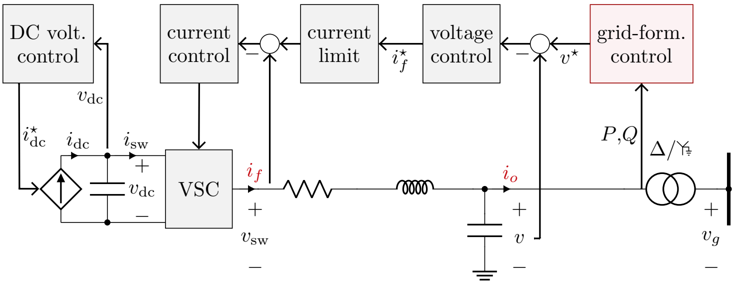



## Grid-forming control (GFC) of DC/AC power converters

- **main principles** and **control strategies**
- **stability** of dVOC in multi-converter / no-inertia systems
- **fast frequency response** vs. **virtual inertia** in low-inertia systems

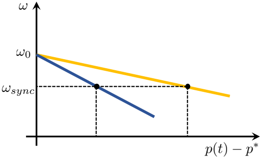
## Open questions & and ongoing work

- **adverse interactions**: converter control, machine control, & network
- GFC for sources with **limited flexibility** & hybrid **DC/AC** systems
- converter **current limits** and **fault response** (not today)



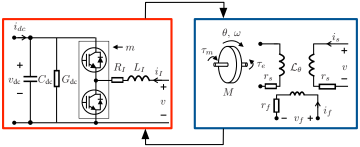

- **Assumption:** DC source controls **DC voltage** to **constant** reference
- **GFC measures power** injection $P,Q$ (or current $i_o$ in $\alpha\beta$-frame)
- **GFC provides AC voltage** reference $\angle v^\star = \theta$, $\|v^\star\| = V$ (or $v^\star_{\alpha\beta}$ in $\alpha\beta$-frame)
- **inner**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

# Grid-forming converter control approaches



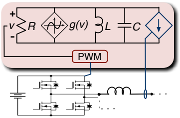

droop control

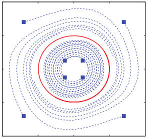
+ intuitive & good small-signal performance
− stability & performance certificates




synchronous machine emulation

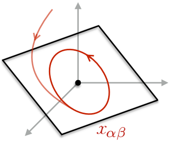
+ (supposedly) backward compatible
− fast converter emulates slow machine



virtual oscillator control (VOC)

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




dispatchable VOC (dVOC)

+ power & voltage specifications
+ strong theoretical guarantees

# dispatchable VOC for multi-converter systems

# dVOC for multi-converter systems

## Grid-forming voltage reference dynamics [1]

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

## 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** $\max_k \sum_j \| Y_{jk} \|$ $\times$ **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 ($\pi$-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 $\omega_0$.

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

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

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

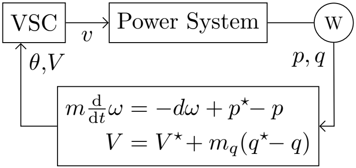
## transmission system ($r_{jk} = 0$, $\|v\| \approx v^\star$) $\approx$ droop control [Chandorkar, Divan, Adapa, '93]

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

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

[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)

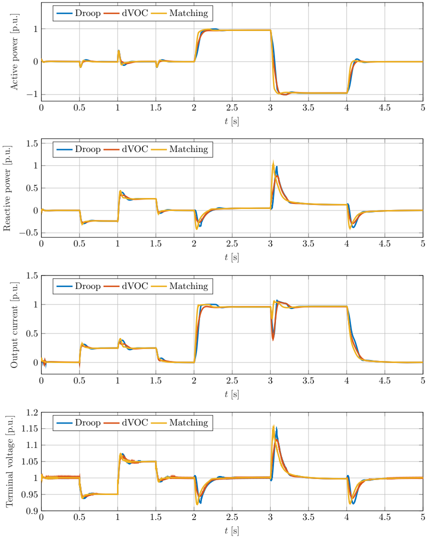



**Grid-forming:** $(P, Q) \to (\omega, V)$

- 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

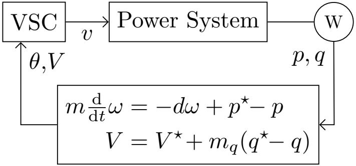
  $\to$ $m$ typically **very small**

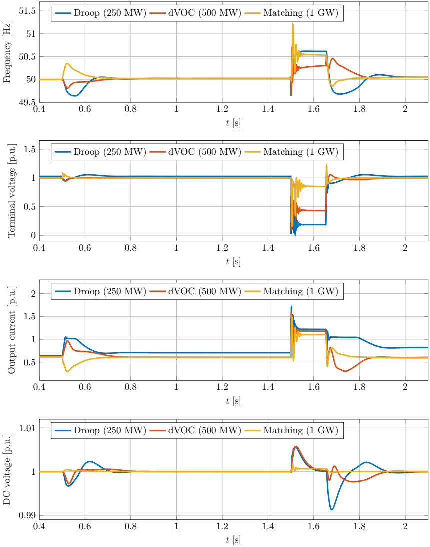
- **similar** reduced-order **models**




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

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




**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

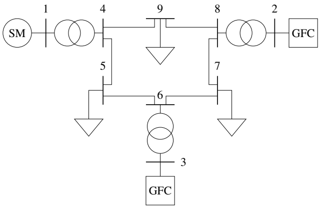
  $\to$ $m$ typically **very small**

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

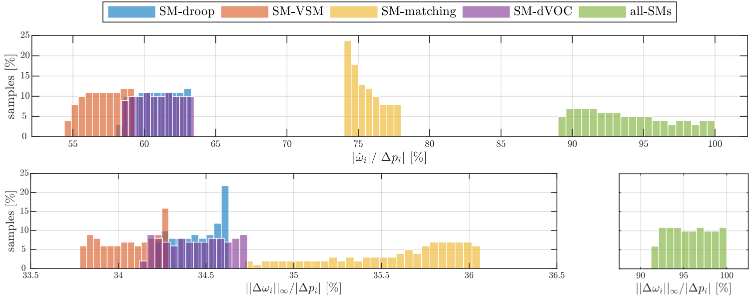
[1] MIGRATE Deliverable 3.3: *New options for existing system services and needs for new system services*, 2018

# The role of inertia in low-inertia systems

# 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

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

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

$$
\begin{aligned}
\tfrac{\mathrm{d}}{\mathrm{d}t}\theta_{\mathsf{GFC}} &= (\nu d_{\mathsf{GFC}})^{-1} b(\theta_{\mathsf{SM}} - \theta_{\mathsf{GFC}}) \\
\tfrac{\mathrm{d}}{\mathrm{d}t}\theta_{\mathsf{SM}} &= \omega_{\mathsf{SM}} \\
(1-\nu) 2H \tfrac{\mathrm{d}}{\mathrm{d}t}\omega_{\mathsf{SM}} &= -b(\theta_{\mathsf{SM}} - \theta_{\mathsf{GFC}}) + p_\tau - p_l \\
\tau \tfrac{\mathrm{d}}{\mathrm{d}t} p_\tau &= -p_\tau - (1-\nu) d_{\mathsf{SM}} \omega
\end{aligned}
$$

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

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

- share of GFC relative to overall rating: $\nu \in (0, \frac{2}{3}]$
- change coordinates to relative angle $\delta = \theta_{\text{SM}} - \theta_{\text{GFC}}$

$$\begin{aligned}
\tfrac{\mathrm{d}}{\mathrm{d}t}\theta_{\text{GFC}} &= (\nu d_{\text{GFC}})^{-1} b(\theta_{\text{SM}} - \theta_{\text{GFC}}) \\
\tfrac{\mathrm{d}}{\mathrm{d}t}\theta_{\text{SM}} &= \omega_{\text{SM}} \\
(1-\nu)2H\tfrac{\mathrm{d}}{\mathrm{d}t}\omega_{\text{SM}} &= -b(\theta_{\text{SM}} - \theta_{\text{GFC}}) + p_\tau - p_l \\
\tau\tfrac{\mathrm{d}}{\mathrm{d}t}p_\tau &= -p_\tau - (1-\nu)d_{\text{SM}}\omega
\end{aligned}$$

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

# Simplified / qualitative analysis

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

- share of GFC relative to overall rating: $\nu \in (0, \frac{2}{3}]$
- change coordinates to relative angle $\delta = \theta_{\mathsf{SM}} - \theta_{\mathsf{GFC}}$

$$\begin{aligned}
\tfrac{\mathrm{d}}{\mathrm{d}t}\delta &= \omega_{\mathsf{SM}} - (\nu\, d_{\mathsf{GFC}})^{-1} b\delta \\
(1-\nu)2H\tfrac{\mathrm{d}}{\mathrm{d}t}\omega_{\mathsf{SM}} &= -b\delta + p_\tau - p_l \\
\tau\tfrac{\mathrm{d}}{\mathrm{d}t}p_\tau &= -p_\tau - (1-\nu)\, d_{\mathsf{SM}}\omega
\end{aligned}$$

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

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

- share of GFC relative to overall rating: $\nu \in (0, \frac{2}{3}]$
- change coordinates to relative angle $\delta = \theta_{\text{SM}} - \theta_{\text{GFC}}$
- $H$ and $\tau$ are large $\rightarrow$ eliminate "fast" angle dynamics (COI model)

$$
\begin{aligned}
\frac{\mathrm{d}}{\mathrm{d}t}\delta &= \omega_{\text{SM}} - (\nu\, d_{\text{GFC}})^{-1} b\delta \\
(1-\nu)2H\frac{\mathrm{d}}{\mathrm{d}t}\omega_{\text{SM}} &= -b\delta + p_\tau - p_l \\
\tau\frac{\mathrm{d}}{\mathrm{d}t}p_\tau &= -p_\tau - (1-\nu)\, d_{\text{SM}}\omega
\end{aligned}
$$

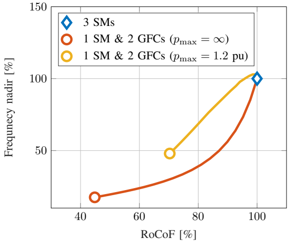
[1] Tayyebi, Groß, Anta, Kupzog, Dörfler: *Frequency Stability of Synchronous Machines and Grid-Forming Power Converters*, IEEE JESTPE, 2020

# Simplified / qualitative analysis

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

- share of GFC relative to overall rating: $\nu \in (0, \frac{2}{3}]$
- change coordinates to relative angle $\delta = \theta_{\mathsf{SM}} - \theta_{\mathsf{GFC}}$
- $H$ and $\tau$ are large $\rightarrow$ eliminate "fast" angle dynamics (COI model)

$$(1-\nu) 2H \tfrac{\mathrm{d}}{\mathrm{d}t}\omega_{\mathsf{SM}} = \nu \, d_{\mathsf{GFC}} \omega_{\mathsf{SM}} + p_\tau - p_l$$
$$\tau \tfrac{\mathrm{d}}{\mathrm{d}t} p_\tau = -p_\tau - (1-\nu) \, d_{\mathsf{SM}} \omega$$

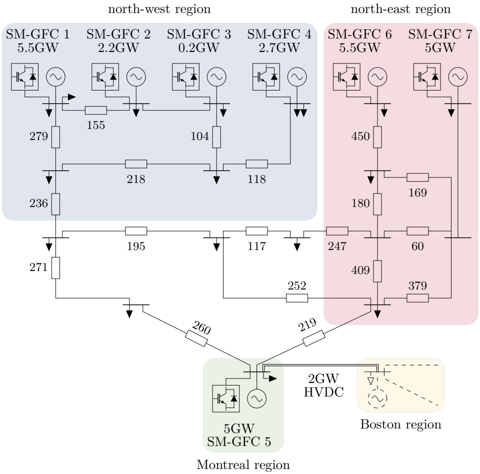



$\Rightarrow$ Fast frequency response replaces slow SM turbine/governor

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

# Too good to be true?

# Simplified model of Quebec region




## Synchronous machines

- 8-th order model
- hydraulic turbine
- governor with 5% droop
- AVR & MB-PSS (type 4B)

## Two-level VSCs

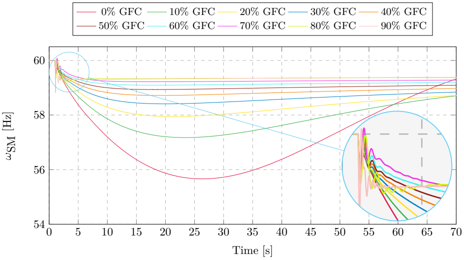
- Aggregate of many VSC modules
- P-f droop control
- DC source (limits & resp. time)

## Definition: integration level

$$\eta = \frac{\sum_{i=1}^{7} S_{\mathsf{GFC}_i}}{\sum_{i=1}^{7} (S_{\mathsf{GFC}_i} + S_{\mathsf{SM}_i})}$$

[1] A. Crivellaro, A. Tayyebi, C. Gavriluta, D. Groß, A. Anta, F. Kupzog, F. Dörfler: *Beyond low-inertia systems: Massive integration of grid-forming power converters in transmission grids*, best paper award at IEEE PES GM 2020

# Uniform transition from 100% SMs to 100% grid-forming VSCs




**Loss of 5.5 GW (SM 1):** $0 \geq \eta \geq 0.9$

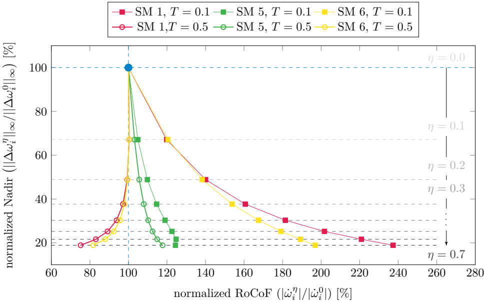
- max. contingency for small $\eta$
- frequency of SM 2 for different $\eta$
- increased $\eta \rightarrow$ **better nadir**
- PSS retuning for $\eta \geq 0.8$

- multi-machine system
  - **turbine too slow** to suppress frequency **oscillations**
  - **PSS suppresses** frequency **oscillations** through voltage control
- multi-machine multi-converter system
  - PSS **lead-lag compensator** acts on fast **GFC response**


[1] A. Crivellaro, A. Tayyebi, C. Gavriluta, D. Groß, A. Anta, F. Kupzog, F. Dörfler: *Beyond low-inertia systems: Massive integration of grid-forming power converters in transmission grids*, IEEE PES GM 2020

[2] Markovic, Stanojev, Aristidou, Vrettos, Callaway, Hug: *Understanding Small-Signal Stability of Low-Inertia Systems*, IEEE TPWRS, 2021.

# Frequency metrics & protection




Nadir and RoCoF for a loss of 2 GW (HVDC link)

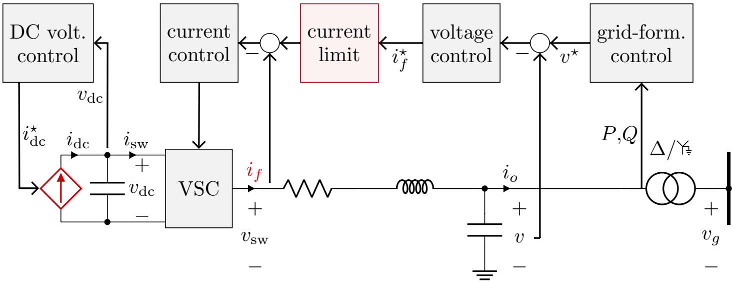
## Frequency nadir & averaged RoCoF

- RoCoF averaged over $T = \{0.1, 0.5\}$
- SM 1 and SM 6 far from event
  - $T = 0.1$: RoCoF deteriorates
  - $T = 0.5$: RoCoF improves
- SM 5 adjacent to event
  - largest absolute RoCoF
  - insensitive to $T$
- GFC freq. show no patterns

- large RoCoF not problematic for GFCs (no rotating parts)
- potentially problematic for machines and grid-following converters
- RoCoF not a reliable protection signal: inertia emulation vs. updated protection?

# GFC for sources with limited flexibility & hybrid DC/AC systems

# Standard grid-forming VSC control architecture



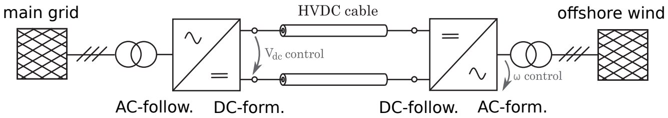

- **cascaded PI** controllers track **voltage reference** $\angle v^\star = \theta$, $\|v^\star\| = V$
- **AC current limited** by **current control** & low-level **protection**

**Limitations of state-of-the art grid-forming control**

- **overloaded** DC **source** $\rightarrow$ **DC & AC voltage collapse**
- **grid-forming** control cut off by **current limiter** $\rightarrow$ **instability**

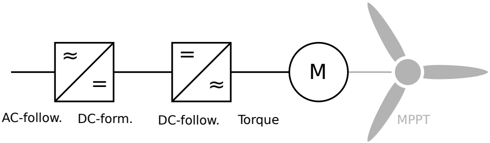
# Future systems: DC, AC, and sources with limited flexibility

## High voltage DC transmission



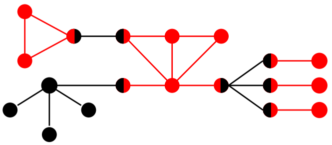

- mix of grid-forming and grid-following converters
- assignment of roles is non-trivial in meshed networks

## Flywheel or wind-turbine with back-to-back converter




- how to leverage the grid-forming capabilities
- roles may be different at different operating points

# Simultaneous AC and DC grid-forming control for DC/AC converters



- ac nodes and edges (red)
- dc nodes and edges (black)
- converter nodes (red/black)

## Nodes categorized by frequency / DC voltage damping capabilities

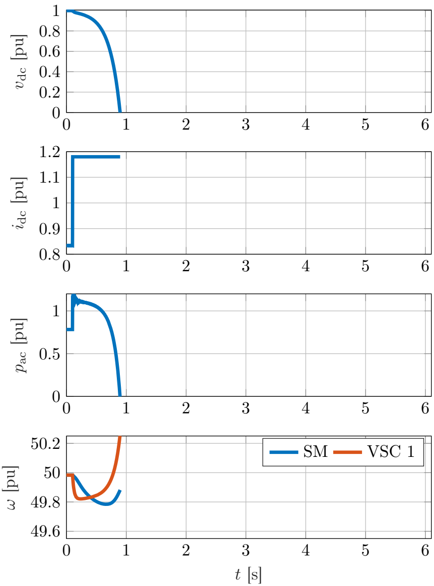
- insignificant: sync. condenser, wind-turbine/PV (MPPT), flywheel, ultracapacitor
- significant: wind-turbine/PV (curtailed), sync. machine with turbine/governor

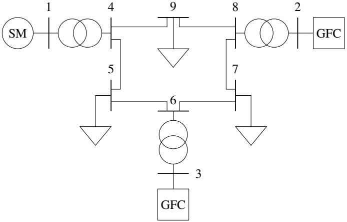
## Simultaneous AC and DC grid-forming control

$$\omega - \omega_0 = m_p(p_{\mathrm{ac}}^{\star} - p_{\mathrm{ac}}) + m_{\mathrm{dc}}(v_{\mathrm{dc}} - v_{\mathrm{dc}}^{\star})$$

- maps power imbalance signal between AC ($\omega - \omega_0$) and DC ($v_{\mathrm{dc}} - v_{\mathrm{dc}}^{\star}$)
- P-f droop term provides angle damping (and P-f droop if $v_{\mathrm{dc}} \approx v_{\mathrm{dc}}^{\star}$)
- stability conditions on AC connections between nodes with/without damping
- cover most realistic topologies (MTDC, wind/PV farms, B2B flywheels, ...)

# Case study: overloaded PV (IEEE 9-bus with 1 SM & 2 VSCs)

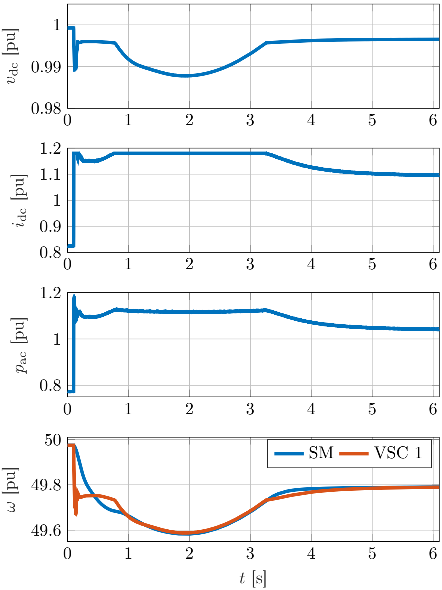


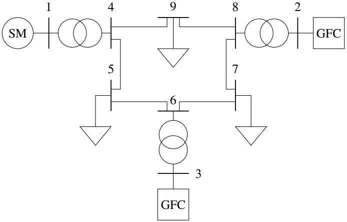




### large load step ($0.9$ pu) at bus 7

- curtailed PV (above MPP volt.):
  - prop. DC volt. control with saturation
- droop control overloads PV:
  - DC volt. collapse & instability in $< 1$ s

# Case study: overloaded PV (IEEE 9-bus with 1 SM & 2 VSCs)




**large load step ($0.9$ pu) at bus 7**

- curtailed PV (above MPP volt.):
  - prop. DC volt. control with saturation
- droop control overloads PV:
  - DC volt. collapse & instability in $< 1$ s
- simultaneous DC & AC grid-forming
  - PV limited: “sync. condenser”
  - otherwise: primary freq. control

# Take home messages

## 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)
- mix of SMs, GFL, GFC: **instability** due to adverse interactions across **time-scales** and **different devices**

## Frequency stability and RoCoF protection challenges

- GFCs have **no rotating parts**: high RoCoF **no longer** indicates a **problem**
- **expensive** inertia **emulation** vs. protection **redesign**?

## Current work & outlook

- GFC for sources with **limited flexibility** & hybrid **DC/AC** systems
- **simultaneous** AC and DC **grid-forming** control for VSCs and MMCs
- **fault response** & AC **current limits** of GFCs (PSERC-S95 with M. Saeedifard)

# Questions?

Dominic Groß

dominic.gross@wisc.edu