Towards grid-forming control for fault and overload ride through

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We are replacing the foundation of today's grid

fuel

− emissions & centralized

renewables

+ sustainable & decentralized

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fuel & synchronous machines

- − **emissions** & **centralized**
- \+ **fully controllable** generation

renewables & power electronics

- \+ **sustainable** & **decentralized**
- − **intermittent** & **limited** generation

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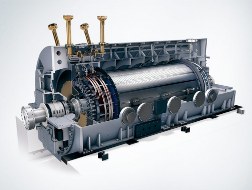

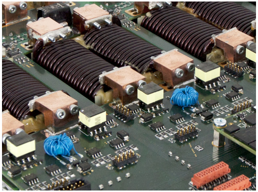

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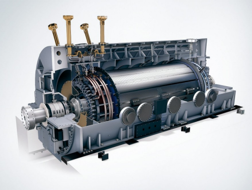

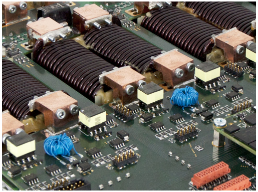

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- − emissions & centralized
- + fully controllable generation
- + interoperable physics (& controls)
- + large fault current & FRT well understood

renewables & power electronics

- + sustainable & decentralized
- − intermittent & limited generation
- − heterogeneous & fragile controls
- − low overcurrent & FRT poorly understood

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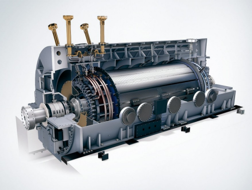

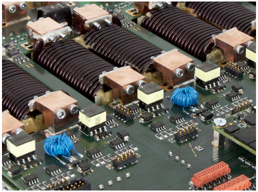

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− **emissions** & **centralized**

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− **intermittent** & **limited** generation

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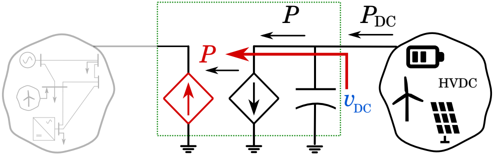
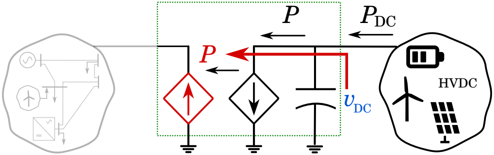
\+ **fast** actuation & **flexible** control

Grid-following vs. Grid-forming control



Basic assumptions

- **assumption:** AC power system is an **infinite AC bus**
- **converter model:** **AC current source** feeding into an **infinite AC bus**



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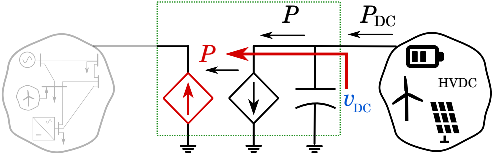
- **PV & Wind:** stabilize renewable source & track **maximum power point**
- **HVDC:** stabilize DC voltage & track **power reference**

Grid-following control: renewables & maximum power point tracking



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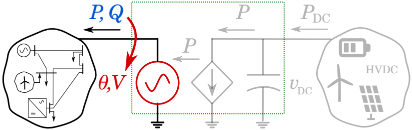
Constraint handling through control of grid current

- **converter limits:** clip **reference currents**, momentary cessation, ...
- **power source limits:** control of **power injection**

Grid-forming (GFM) control: the cornerstone of future grids?



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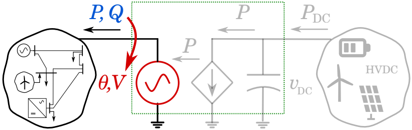

Droop control [1]

$$\omega_k - \omega_0 = m_p \left(p_k^\star - p_{\text{ac},k} \right)$$

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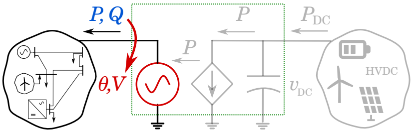

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- **autonomous disturbance response:** stabilize **frequency & voltage**

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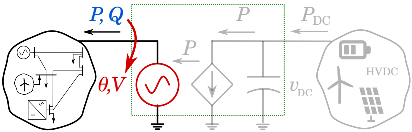

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Constraint handling through control of grid current

- many **heuristics** for **current** limiting under **faults**
- few works on **dc voltage**, modulation, & **power source** constraints
- interaction of **device-level** protection and **system-level** protection?

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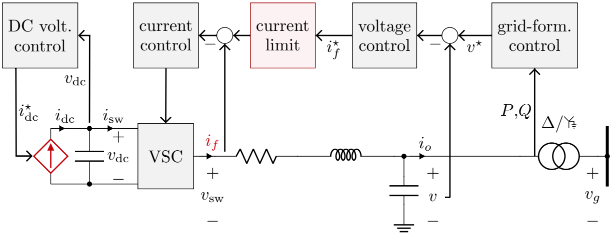
Standard GFM control architecture for two-level VSCs



Cascaded dual-loop vector control & assumptions

- **outer** GFM control provides **voltage reference** $\angle v^\star = \theta$, $\|v^\star\| = V$
- **inner** current and voltage control used to track GFM voltage reference
- DC bus **controlled** through DC source

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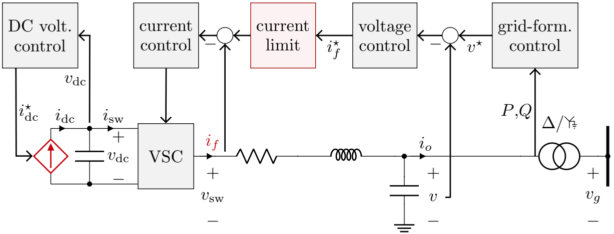

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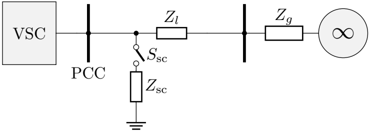
Functions of inner control loops

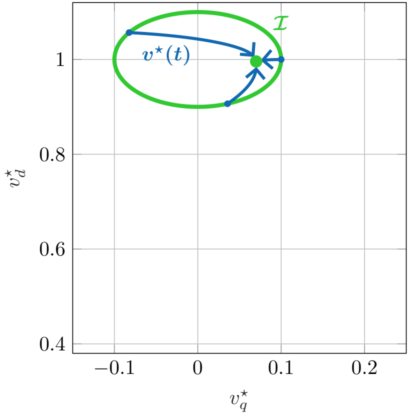
- **stiff** control of ac capacitor voltage **phase angle** & **magnitude**
- **damping** of filter **resonance** & enforcing **timescale separation**
- explicit **current control** & **current limiting**

Simple example: loss of synchronization



GFM & standard current limiting

- set of voltages $\mathcal{I}$ for which $\|i_f\| \leq I_{\max}$
- normal operation:
  - GFM control points inside $\mathcal{I}$
  - current limit never active



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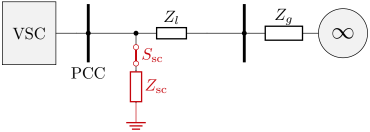

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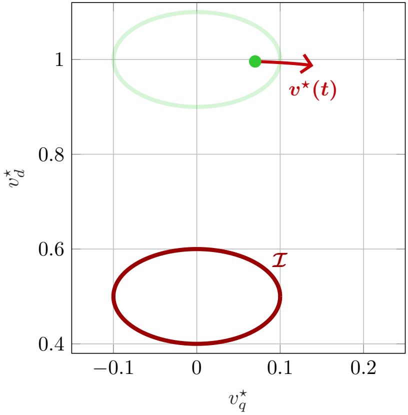
  - current limiter drives voltage to $\mathcal{I}$
  - loss of tracking & GFM synchronization



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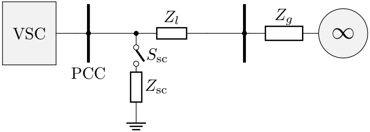

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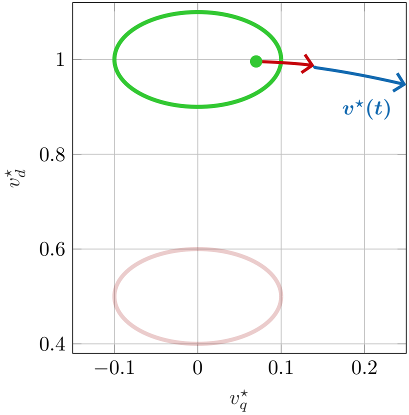
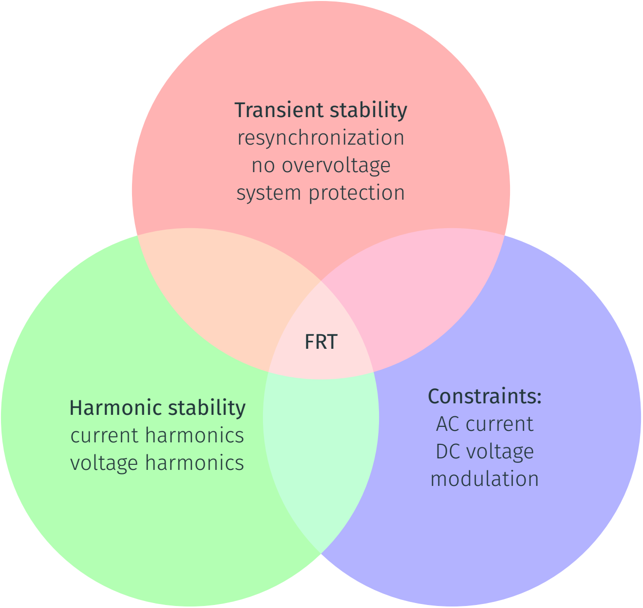
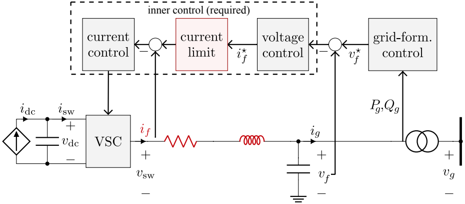


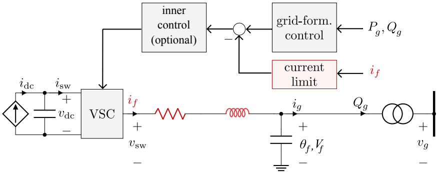
Current limiting $\neq$ fault ride through



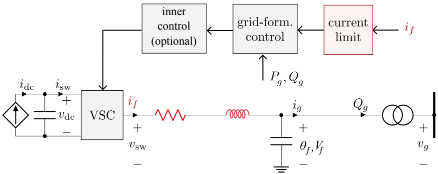
GFM control architectures revisited



- reuse GFL architecture
- industry standard (?)
- loss of synchronization

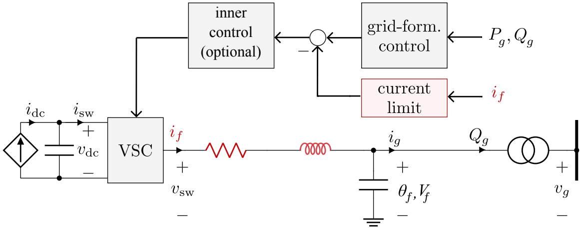


- well-studied in academia
- virt. impedance heuristics
- largely avoids loss of sync.



- very early stage
- no loss of sync.
- harmonic stability?

GFM control architecture with parallel limiter



Cascaded dual-loop vector control (optional)

- **outer** GFM control provides **voltage reference** $\angle v^{\star} = \theta$, $\|v^{\star}\| = V$
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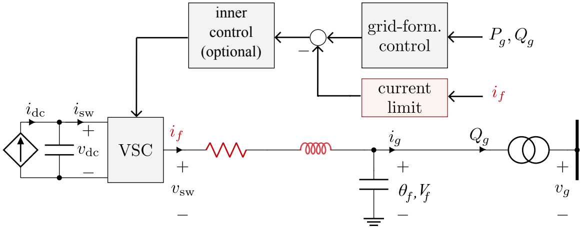

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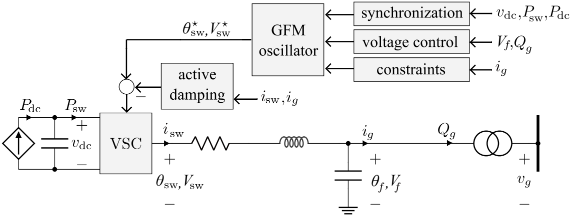
Threshold virtual impedance

- **emulates increasing** filter **impedance** as current approaches limit
- retains **self-sync. voltage source** dynamics behind **variable impedance**

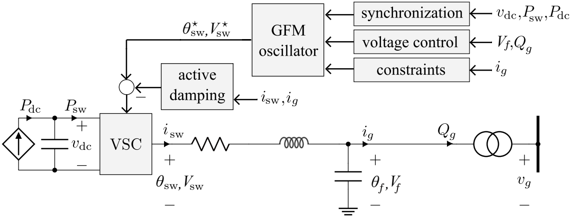
GFM control architecture with outer limiter



Active damping for harmonic stability (optional)

- "modifies" **circuit** to compensate filter/grid **resonance** & harmonics

GFM control architecture with outer limiter



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Inner GFM oscillator

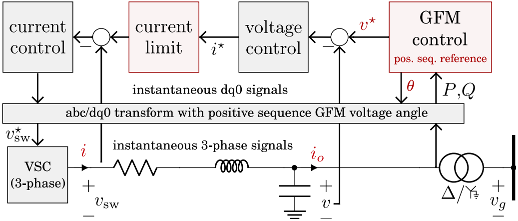
- GFM **voltage reference** $\angle v^\star = \theta$, $\|v^\star\| = V$ **always** tracked by VSC

Outer loops: self-synchronization & constraints

- **synchronization** of GFM oscillator states (e.g., $P - f$ droop)
- **control** of terminal **voltage magnitude** (e.g., $Q - V$ droop)
- **constraint** handling functions (e.g., current, modulation, dc voltage)

Unbalanced fault ride through

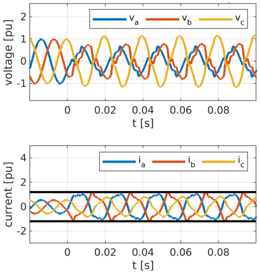
- standard grid-forming control aims to impose balanced voltage
- does not allow full control of current in unbalanced system
- grid-forming control of symmetric components? phase voltages?



Relative Number of Different Types of Faults on HV Transmission Lines

Fault Types	Percent
Single Phase-to-Ground Faults	70
Phase-to-Phase Faults	15
Double Phase-to-Ground Faults	10
Three Phase Faults	5

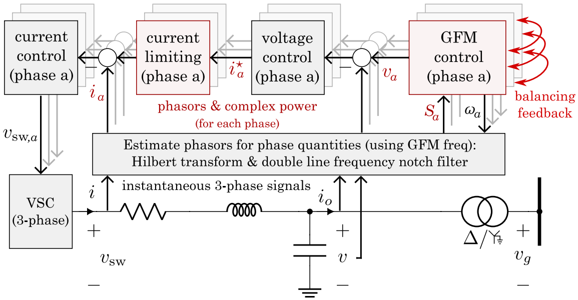
Reference current limiting (A-g fault)



Coordinate frames for GFM control

Generalized GFM control leverages flexibility of VSCs

- pos./neg. sequence: intuitive for protection but VSC limits are per phase
- per-phase: straightforward handling of VSC limits
- per-phase can be abc or Clarke coordinates (e.g., $\alpha\beta$)
- requires estimation of ”phasors” for pos./neg. sequence or abc



Outline for the presentation

(some) results from S-95

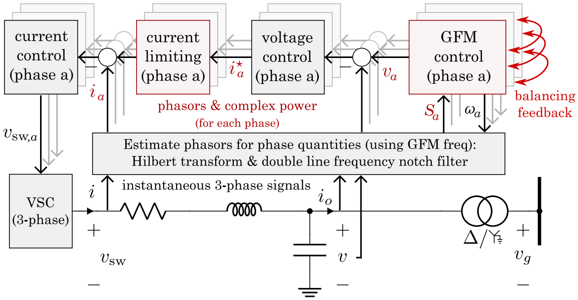
- unbalanced fault ride-through
- interaction with system-level protection

recent results on constrained GFM

- architecture with outer constraint handling
- preliminary results for the balanced case

S-95: Reliable fault ride-through and protection of converter-dominated power systems under unbalanced conditions

Generalized three-phase grid-forming control



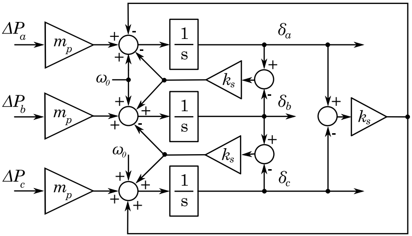
- estimation and grid-forming control for every phase (DC midpoint grounded)
- phase-balancing feedback between single-phase grid-forming controls
- dual-loop current and voltage control
- current reference limiting or threshold virtual impedance for every phase

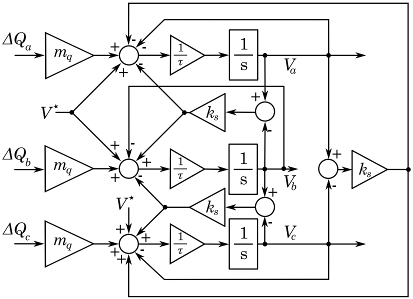
- single-phase droop for every phase $p \in \{a, b, c\}$ & phase-balancing

$$\frac{\mathrm{d}}{\mathrm{d}t}\delta_p^{\mathsf{gfm}} = \omega_0 + m_P(P_p^\star - P_p) - \sum_{l \in \mathcal{P}\setminus p} k_P(\delta_p^{\mathsf{gfm}} - \delta_l^{\mathsf{gfm}})$$

$$\tau \frac{\mathrm{d}}{\mathrm{d}t} V_{\delta,p}^{\mathsf{gfm}} = -V_{\delta,p}^{\mathsf{gfm}} + m_Q(Q_p^\star - Q_p) - \sum_{l \in \mathcal{P}\setminus p} k_Q(V_{\delta,p}^{\mathsf{gfm}} - V_{\delta,l}^{\mathsf{gfm}})$$

- phase-balancing gains $k_P \in \mathbb{R}_{\geq 0}$ and $k_Q \in \mathbb{R}_{\geq 0}$ control voltage unbalance





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$$\begin{bmatrix} \overline{\omega}_\delta \\ \delta_{a-b} \\ \delta_{b-c} \end{bmatrix} = \begin{bmatrix} -m_p & 0 & 0 \\ 0 & -\frac{m_P}{3k_P} & 0 \\ 0 & 0 & -\frac{m_P}{3k_P} \end{bmatrix} \begin{bmatrix} \overline{P}_\delta \\ P_{a-b} \\ P_{b-c} \end{bmatrix}$$

$$\begin{bmatrix} \overline{V}_\delta \\ V_{b-b} \\ V_{b-c} \end{bmatrix} = \begin{bmatrix} -m_Q & 0 & 0 \\ 0 & -\frac{m_Q}{3k_Q+1} & 0 \\ 0 & 0 & -\frac{m_Q}{3k_Q+1} \end{bmatrix} \begin{bmatrix} \overline{Q}_\delta \\ Q_{a-b} \\ Q_{b-c} \end{bmatrix}$$

GFM control of symmetrical components

$$\Delta\omega^{+} = m_p^{+}(P^{+\star} - P^{+}) \tag{1}$$

$$\Delta\omega^{-} = m_p^{-}(P^{-\star} - P^{-}) \tag{2}$$

$$\Delta V^{+} = m_q^{+}(Q^{+\star} - Q^{+}) \tag{3}$$

$$\Delta V^{-} = m_q^{-}(Q^{-\star} - Q^{-}) \tag{4}$$

- intuitive from protection point of view (?)
- complex limiting due to nonlinear relationship with VSC phase current limits
- does not control neg. sequence current during fault or improve unbalanced FRT
- droop on neg. sequence current allows to control neg. sequence current few tangible benefits over phase control approach

Converter protection

- Current saturation
  - limits current reference (no tuning parameters)
  - Sub-cycle phase current limiting
  - integrator wind-up and loss of synchronization
- Threshold virtual impedance
  - emulates increasing output impedance as current increases
  - difficult to tune: R/X ratio, activation threshold, filter time constants
  - Heuristic for short-circuit faults that can't handle phase jumps (e.g., line opening)

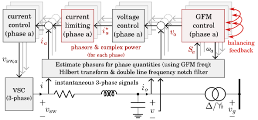


Fig. 1: Three-phase GFM control with current saturation

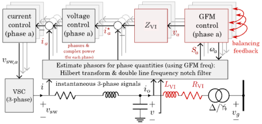


Fig. 2: Three-phase GFM control with threshold virtual impedance (TVI)

Interaction with system protection: Transmission

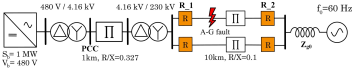


Fig. 1: Transmission system with distance relays

- Low converter rating (1 MW)
- **Distance relay** at the **grid side trips normally**
- **Distance relay** at the **inverter side** may not trip due to **limited IBR fault current capability**
- When the fault resistance is 5 Ω, Relay 1 trips after Relay 2 trips (i.e., the system becomes a single-ended network).

Table 1: Mho Relay Setting

Protection Zone	Percentage of the transmission line	Operation Delay time
Zone 1	20 %	16.7 ms
Zone 2	100 %	100 ms
Zone 3	200 %	400 ms

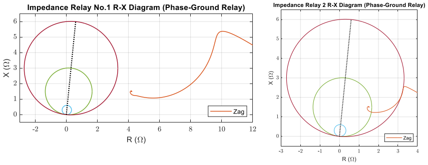


Fig. 3: When R_f = 1 Ω, the impedance computed by relays (before R_2 trips)

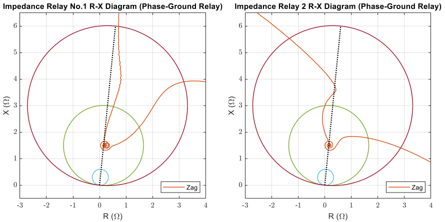


Fig. 3: When R_f = 0.001 Ω, the impedance computed by relays

Distribution System with the Inverse Time Relay

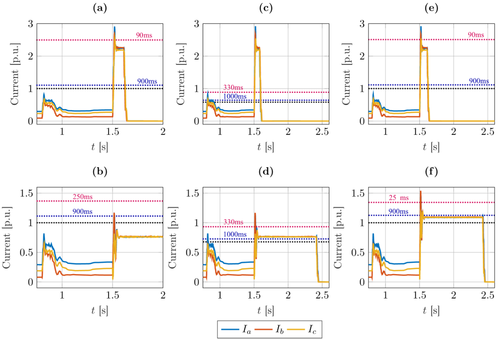


Fig. 2: ABC-g fault with inverse time relay.

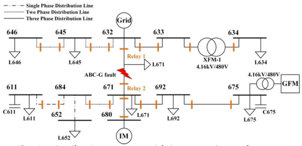


Fig. 1: Distribution system with inverter time relay

- original GFM current limit and protection setting
  - Relay one operates (a)
  - Relay two misoperates (b)
- original GFM current limit and reduced relay threshold
  - reduced thresholds by 30%
  - Both relays operate correctly (c,d)
- original GFM current limit and protection setting
  - GFM current limits increased by 40%
  - Both relays operate correctly (e,f)

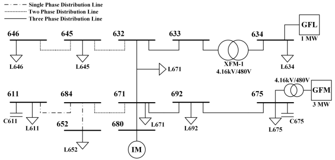


Fig. 1: Single-line diagram of BUS 13 distribution system including one GFM and one GFL

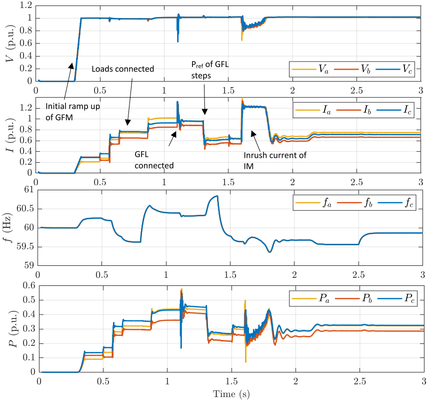


Fig. 2: Simulation results of the cold start

- Distributed cold start with GFM converters: no central control or coordination used
- Loads are connected or disconnected based on local voltage and frequency measurements and time delays
- inrush current during startup of induction machine is limited by current saturation algorithm (CSA)

Take-home messages from S-95

Three-phase GFM fully leverages controllability of three-phase VSCs

- Standard controls and current limiting applied to each phase to control phase current / voltage
- Phase-balancing trades off voltage / power unbalance / sharing of unbalanced load

Benchmark systems to study interaction with system protection

- Transmission benchmark with distance relays
- Distribution benchmark with inverse time relays, UFLS/UVLS, induction machines, GFL, etc.
- Tuning guidelines for protective relays in converter-dominated systems

Improved FRT performance for short-circuit faults

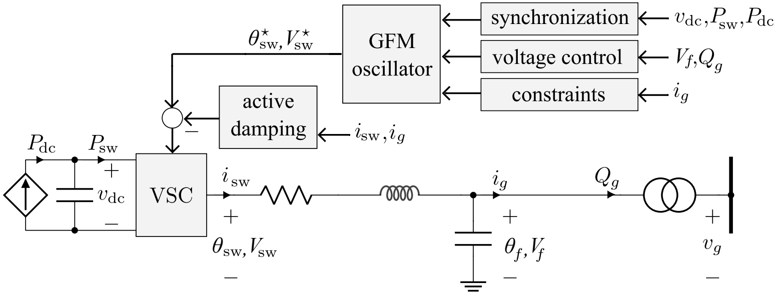
- Tuning methods for virtual impedance
- Hybrid threshold virtual impedance

Distributed cold-start methods for unbalanced distribution feeders using GFM converters

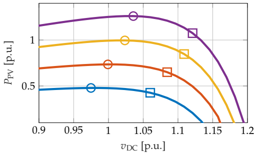
- Cold-start mechanisms that do not rely on centralized coordination

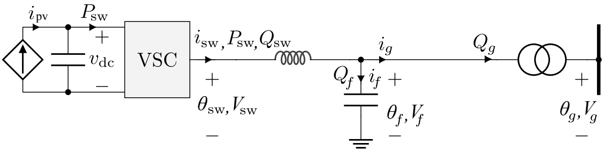
Towards constrained GFM control

Inner loops become outer loops



- GFM voltage oscillator never ”cut off”
- synchronization slowly changes GFM oscillator phase angle
- voltage magnitude control at terminal
- fast control of GFM oscillator to satisfy constraints



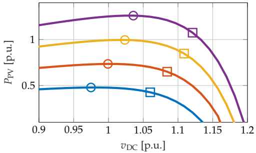


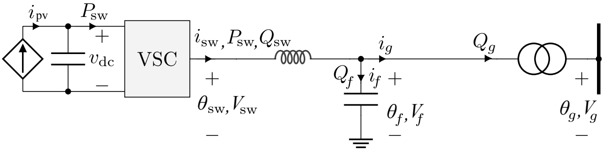
- dc-link dynamics

$$v_{\mathrm{dc}}(t+1) = v_{\mathrm{dc}}(t) + \frac{\tau}{C_{\mathrm{dc}} v_{\mathrm{dc}}^{\star}}(P_{\mathrm{pv}}(t) - P_{\mathrm{sw}}(t))$$

- Quasi-steady-state circuit model
  - PV: $i_{\mathrm{pv}}(t+1) = i_{\mathrm{ph}} - I_0(e^{\frac{q v_{\mathrm{dc}}(t+1)}{\alpha K T}} - 1) - \frac{v_{\mathrm{dc}}(t+1)}{R_{\mathrm{sh}}}$
  - power injection: $P_{\mathrm{sw}}(t) = \frac{b_{\mathrm{sw}} b_{\mathrm{g}}}{b_{\mathrm{sw}} + b_{\mathrm{eq}}}(\theta_{\mathrm{sw}}(t) - \theta_{\mathrm{g}}(t))$, $Q_g = b_{\mathrm{g}}(V_f(t) - V_g(t))$
  - filter voltage: $V_f = \frac{b_{\mathrm{sw}} V_{\mathrm{sw}}(t) + b_{\mathrm{g}} V_{\mathrm{g}}}{b_f + b_{\mathrm{sw}} + b_{\mathrm{g}}}$
  - current: $i_{\mathrm{sw}}(t) = Z_{\mathrm{eq}}(v_{\mathrm{sw}}(t) - v_{\mathrm{g}}(t))$

Models, objectives & constraints for grid-connected PV





$$\min_{\theta_{\mathrm{sw}}(t),\, V_{\mathrm{sw}}(t)} (\omega_{\mathrm{sw}}(t) - \omega_0)^2 + m_{\mathrm{dc}}(v_{\mathrm{dc}}(t+1) - v_{\mathrm{dc}}^\star)^2 + \frac{1}{\tau_v}(V_f(t) - V_f^\star)^2 + \frac{m_q}{\tau_v}(Q_g(t) - Q_g^\star(t))$$

s.t. (circuit model, PV model, dc dynamics)

$$v_{\mathrm{mpp}} \leq v_{\mathrm{dc}}(t+1)$$

$$v_{\max} \geq v_{\mathrm{dc}}(t+1)$$

$$V_{\mathrm{sw}}(t) \leq \frac{\gamma}{2} v_{\mathrm{dc}}(t)$$

$$i_{\mathrm{pv}}(t+1) \geq 0$$

$$\| i_{\mathrm{sw}}(t) \| \leq i_{\max}$$

Objectives and insights from PD-GFM

Power systems standards distinguish nominal and fault response

- nominal: well-understood GFM controls & small-signal dynamics
- constrained: track GFM as close as possible under constraints

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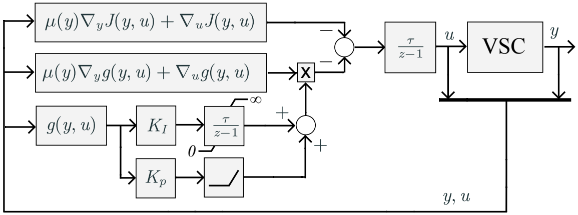
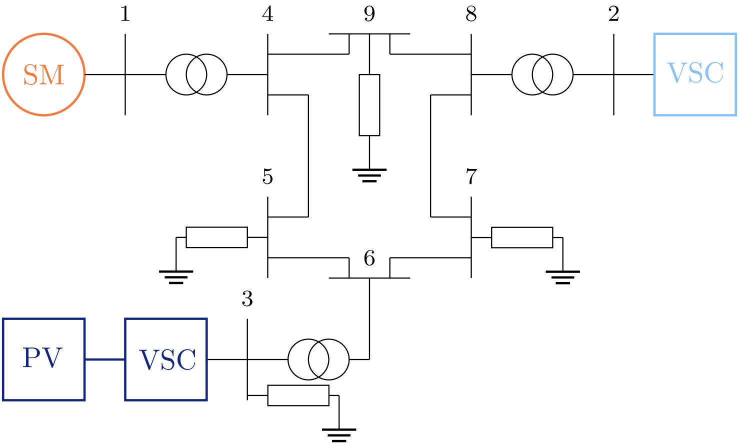


Lessons learned from PD-GFM

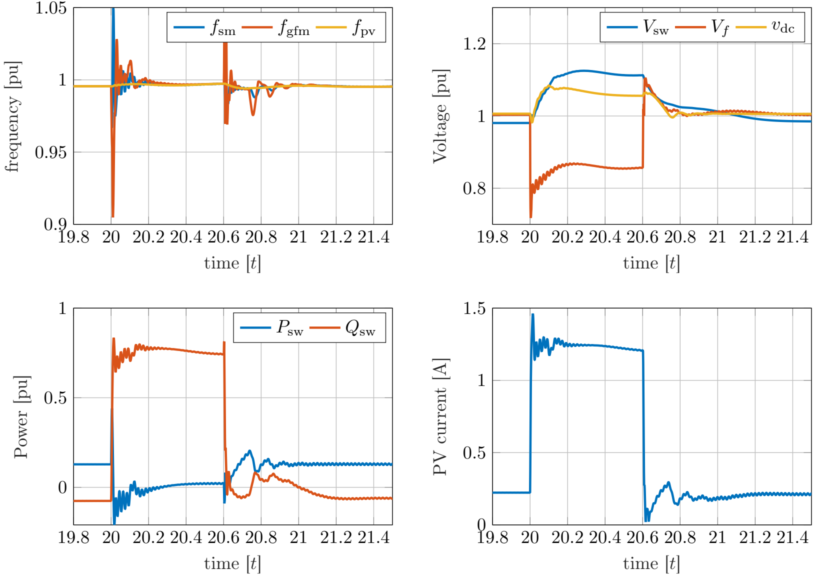
- integral of constraint violation crucial for robustness
- quasi-steady-state model insufficient during faults
- primal-dual gradient descent not converging fast enough

EMT simulation results

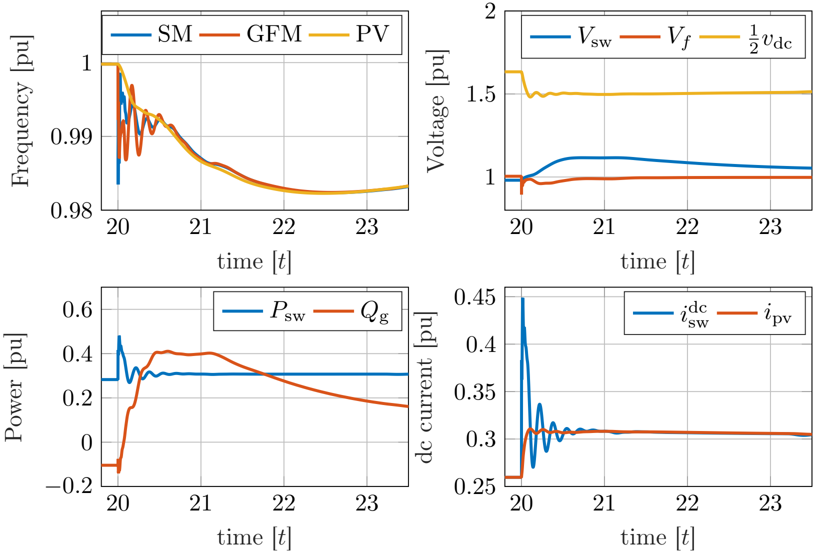


- VSC at bus 3 uses constrained GFM control
- VSC at bus 2 uses dual-port GFM control & energy storage
- various loads and perturbations at bus 3

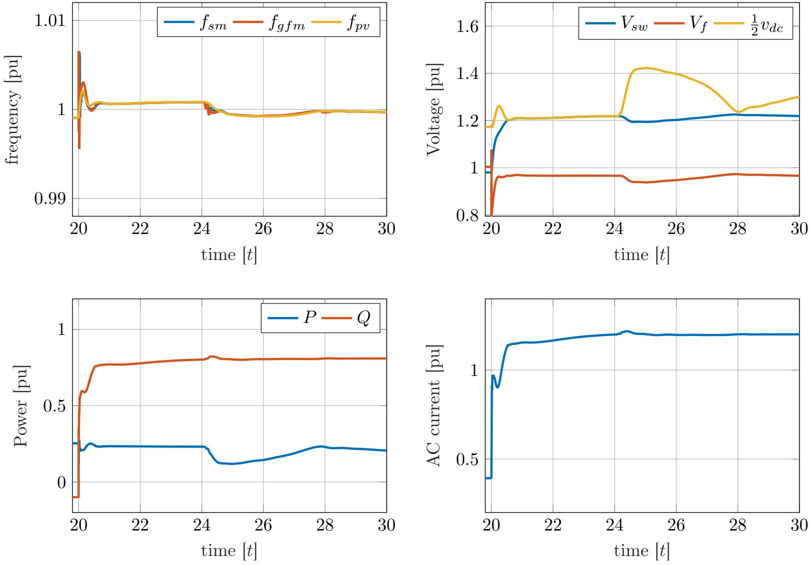
Simulation results: high impedance fault



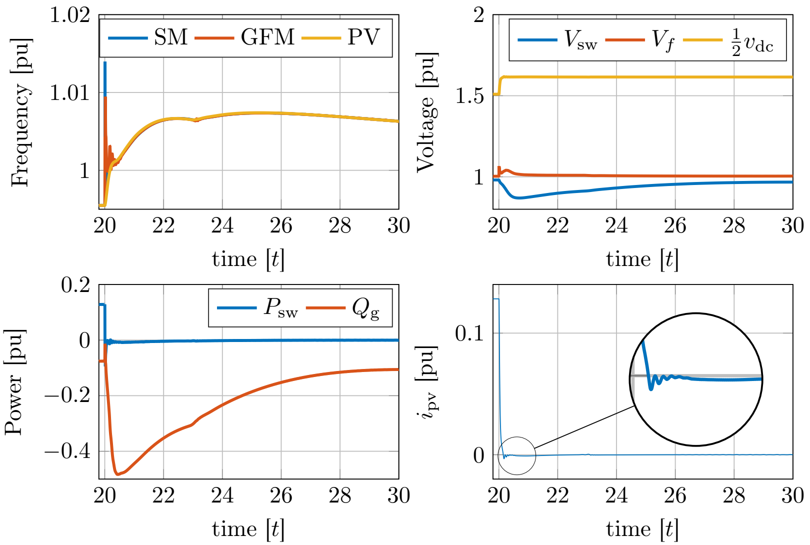
Simulation results: DC voltage limit



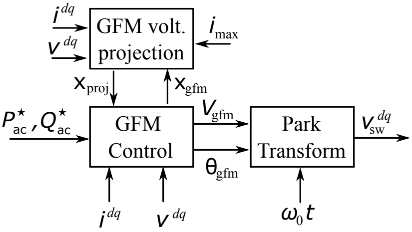
Simulation results: reactive load



Simulation results: reverse PV current



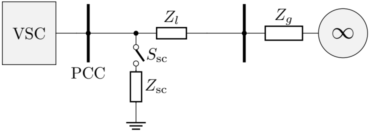
Conceptual implementation



High-level approach

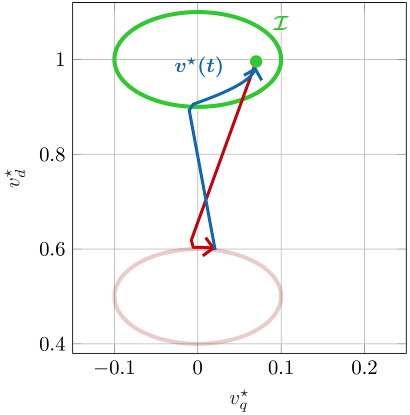
- "outer" GFM control provides small-signal reference
- compute set of VSC voltages that do not violate constraints
  - one-step set: dynamic model of filter circuit
  - steady-state set: using quasi-steady-state model
- reset GFM control state to within constraints
  - restrict GFM control states to one-step set
  - minimize integral of one-step and steady-state constraint violation

Simple example: loss of synchronization

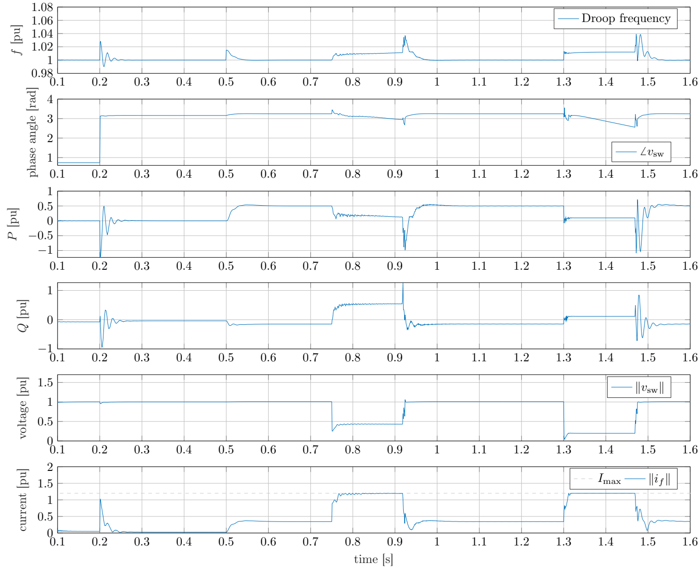


Ideal response?

- execute GFM control
- compute integral of constraint violation
- compute nearest voltage in $\mathcal{I}$ that minimizes integral of constraint violation
- reset GFM control state



Simulation results



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unifi
universal interoperability for grid-forming inverters

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