Towards grid-forming control for fault and overload ride through

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We are replacing the foundation of today’s grid

<table>
<thead>
<tr>
<th>fuel</th>
<th>renewables</th>
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<td>– emissions &amp; centralized</td>
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fuel & synchronous machines
- emissions & centralized
+ fully controllable generation

renewables & power electronics
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- intermittent & limited generation
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+ large fault current & FRT well understood

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- low overcurrent & FRT poorly understood
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  - emissions & centralized
  + fully controllable generation
  + interoperable physics (& controls)
  + large fault current & FRT well understood
  - slow physics & actuation

- renewables & power electronics
  + sustainable & decentralized
  - intermittent & limited generation
  - heterogeneous & fragile controls
  - low overcurrent & FRT poorly understood
  + 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
Grid-following control: renewables & maximum power point tracking

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Control objectives

▶ 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?

\[ P, Q, \theta, V \] \hspace{1cm} \begin{align*}
\omega_k - \omega_0 &= m_p (p^\star_k - p_{ac,k}) \\
&= \sum j b_{kj} (\theta_k - \theta_j)
\end{align*}

Basic assumptions:
▶ assumption: DC terminal is an infinite DC bus
▶ converter model: AC voltage source feeding network (no current limits)

Control objectives:
▶ nominal operation: sync. at \((p^\star, q^\star, V^\star, \omega_0)\) prescribed by operator
▶ autonomous disturbance response: stabilize frequency & voltage

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?

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

Droop control [1]

\[ \omega_k - \omega_0 = m_p \left( p_k^* - p_{ac,k} \right) \]

\[ p_{ac,k} \approx \sum_j b_{kj} (\theta_k - \theta_j) \]

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- **interaction of** device-level protection and system-level protection?

Standard GFM control architecture for two-level VSCs

Cascaded dual-loop vector control & assumptions

- **outer** GFM control provides **voltage reference** \( \angle v^* = \theta, \| v^* \| = V \)
- **inner** current and voltage control used to track GFM voltage reference
- DC bus **controlled** through DC source
Cascaded dual-loop vector control & assumptions

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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 $\|i_f\| \leq I_{\text{max}}$

- normal operation:
  - GFM control points inside $\mathcal{I}$
  - current limit never active
Simple example: loss of synchronization

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- normal operation:
  - GFM control points inside \( \mathcal{I} \)
  - current limit never active
- voltage sag:
  - nominal operating point not in \( \mathcal{I} \)
  - GFM trajectory points outside \( \mathcal{I} \)
  - current limiter drives voltage to \( \mathcal{I} \)
  - loss of tracking & GFM synchronization
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**GFM & standard current limiting**

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Current limiting ≠ fault ride through

**Transient stability**
- Resynchronization
- No overvoltage
- System protection

**Harmonic stability**
- Current harmonics
- Voltage harmonics

**FRT**
- Constraints:
  - AC current
  - DC voltage modulation

Constraints:
- AC current
- DC voltage modulation
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?
Cascaded dual-loop vector control (optional)

- **outer** GFM control provides *voltage reference* $\angle v^* = \theta$, $\|v^*\| = V$
- **inner** current and voltage control used to track GFM voltage reference
- **damping** of filter *resonance* & harmonic stability
- no explicit *current limiting* in inner loops
GFM control architecture with parallel limiter

Cascaded dual-loop vector control (optional)

- **outer** GFM control provides voltage reference $\angle v^* = \theta, \|v^*\| = V$
- **inner** current and voltage control used to track GFM voltage reference
- **damping** of filter resonance & harmonic stability
- **no explicit current limiting** in inner loops

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

Active damping for harmonic stability (optional)

▶ "modifies" circuit to compensate filter/grid resonance & harmonics

Inner GFM oscillator

▶ GFM voltage reference $\angle v^* = \theta$, $\|v^*\| = V$ 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?

Reference current limiting (A-g fault)

| 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       |
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
Generalized three-phase grid-forming control

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

$$\frac{d}{dt} \delta_{gfm}^{p} = \omega_{0} + m_{P}(P_{p}^{*} - P_{p}) - \sum_{l \in \mathcal{P} \setminus p} k_{P}(\delta_{gfm}^{p} - \delta_{gfm}^{l})$$

$$\tau \frac{d}{dt} V_{gfm}^{\delta,p} = -V_{gfm}^{\delta,p} + m_{Q}(Q_{p}^{*} - Q_{p}) - \sum_{l \in \mathcal{P} \setminus p} k_{Q}(V_{gfm}^{\delta,p} - V_{gfm}^{\delta,l})$$

- phase-balancing gains $k_{P} \in \mathbb{R}_{\geq 0}$ and $k_{Q} \in \mathbb{R}_{\geq 0}$ control voltage unbalance
Generalized three-phase grid-forming control

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

\[
\frac{d}{dt} \delta_{gfm}^p = \omega_0 + m_P(P_p^* - P_p) - \sum_{l \in \mathcal{P} \setminus p} k_P(\delta_{gfm}^p - \delta_{gfm}^l)
\]

\[
\tau \frac{d}{dt} V_{gfm, \delta} = -V_{gfm, \delta} + m_Q(Q_p^* - Q_p) - \sum_{l \in \mathcal{P} \setminus p} k_Q(V_{gfm, \delta}^p - V_{gfm, \delta}^l)
\]

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

\[
\begin{bmatrix}
\bar{\omega}_\delta \\
\delta_{a-b} \\
\delta_{b-c}
\end{bmatrix} =
\begin{bmatrix}
-m_P & 0 & 0 \\
0 & -\frac{m_P}{3k_P} & 0 \\
0 & 0 & -\frac{m_P}{3k_P}
\end{bmatrix}
\begin{bmatrix}
\bar{P}_\delta \\
P_{a-b} \\
P_{b-c}
\end{bmatrix}
\]

\[
\begin{bmatrix}
\bar{V}_\delta \\
V_{b-b} \\
V_{b-c}
\end{bmatrix} =
\begin{bmatrix}
-m_Q & 0 & 0 \\
0 & -\frac{m_Q}{3k_Q+1} & 0 \\
0 & 0 & -\frac{m_Q}{3k_Q+1}
\end{bmatrix}
\begin{bmatrix}
\bar{Q}_\delta \\
Q_{a-b} \\
Q_{b-c}
\end{bmatrix}
\]
GFM control of symmetrical components

\[ \Delta \omega^+ = m_p^+(P^{+*} - P^+) \]  \hspace{1cm} (1)
\[ \Delta \omega^- = m_p^-(P^{-*} - P^-) \]  \hspace{1cm} (2)
\[ \Delta V^+ = m_q^+(Q^{+*} - Q^+) \]  \hspace{1cm} (3)
\[ \Delta V^- = m_q^-(Q^{-*} - Q^-) \]  \hspace{1cm} (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

![Diagram of transmission system with distance relays](image)

**Table 1: Mho Relay Setting**

<table>
<thead>
<tr>
<th>Protection Zone</th>
<th>Percentage of the transmission line</th>
<th>Operation Delay time</th>
</tr>
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<tbody>
<tr>
<td>Zone 1</td>
<td>20 %</td>
<td>16.7 ms</td>
</tr>
<tr>
<td>Zone 2</td>
<td>100 %</td>
<td>100 ms</td>
</tr>
<tr>
<td>Zone 3</td>
<td>200 %</td>
<td>400 ms</td>
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- 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).

![Impedance Relay No.1 R-X Diagram (Phase-Ground Relay)](image)

**Fig. 1**: Transmission system with distance relays

**Fig. 3**: When $R_f = 1 \, \Omega$, the impedance computed by relays (before R_2 trips)

![Impedance Relay No.2 R-X Diagram (Phase-Ground Relay)](image)

**Fig. 3**: When $R_f = 0.001 \, \Omega$, the impedance computed by relays
Distribution System with the 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. 2: ABC-g fault with inverse time relay.
Cold Start of an Unbalanced Distribution System

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

- 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)

Fig. 2: Simulation results of the cold start
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
Models, objectives & constraints for grid-connected PV

▶ dc-link dynamics

\[
v_{dc}(t + 1) = v_{dc}(t) + \frac{\tau}{C_{dc}v_{dc}^*} (P_{pv}(t) - P_{sw}(t))
\]

▶ Quasi-steady-state circuit model

- PV: \(i_{pv}(t + 1) = i_{ph} - I_0(e^{\frac{qv_{dc}(t+1)}{\alpha kT}} - 1) - \frac{v_{dc}(t+1)}{R_{sh}}\)
- power injection: \(P_{sw}(t) = \frac{b_{sw}b_g}{b_{sw} + b_{eq}}(\theta_{sw}(t) - \theta_g(t))\), \(Q_g = b_g(V_f(t) - V_g(t))\)
- filter voltage: \(V_f = \frac{b_{sw} V_{sw}(t) + b_g V_g}{b_f + b_{sw} + b_g}\)
- current: \(i_{sw}(t) = Z_{eq}(v_{sw}(t) - v_g(t))\)
Models, objectives & constraints for grid-connected PV

\[
\begin{align*}
& \text{min}_{\theta_{sw}(t), V_{sw}(t)} \left( \omega_{sw}(t) - \omega_0 \right)^2 + m_{dc}(v_{dc}(t + 1) - v_{dc}^*)^2 + \frac{1}{\tau_v} (V_f(t) - V_f^*)^2 + \frac{m_q}{\tau_v} (Q_g(t) - Q_g^*) \\
& \text{s.t.} \quad \begin{cases}
    v_{mpp} & \leq v_{dc}(t + 1) \\
    v_{max} & \geq v_{dc}(t + 1) \\
    V_{sw}(t) & \leq \frac{\gamma}{2} v_{dc}(t) \\
    i_{pv}(t + 1) & \geq 0 \\
    \|i_{sw}(t)\| & \leq i_{max}
\end{cases}
\end{align*}
\]
Objectives and insights from PD-GFM

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<th>Power systems standards distinguish nominal and fault response</th>
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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

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

- Frequency [pu]
- Voltage [pu]
- Power [pu]
- PV current [A]
Simulation results: DC voltage limit

### Frequency [pu]
- SM
- GFM
- PV

### Voltage [pu]
- $V_{sw}$
- $V_f$
- $\frac{1}{2}v_{dc}$

### Power [pu]
- $P_{sw}$
- $Q_g$

### dc current [pu]
- $i_{dc}^\text{sw}$
- $i_{pv}$
Simulation results: reactive load

![Graphs showing simulation results for various parameters such as frequency, voltage, power, and AC current.](image-url)
Simulation results: reverse PV current

- Frequency
  - SM
  - GFM
  - PV

- Voltage
  - $V_{sw}$
  - $V_f$
  - $\frac{1}{2}v_{dc}$

- Power
  - $P_{sw}$
  - $Q_g$

- PV current
  - $i_{pv}$
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

- Droop frequency
- Phase angle [rad]
- Power [pu]
- Reactive power [pu]
- Voltage [pu]
- Current [pu]
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