Powering the Future: Grid-Forming Converter Technology and Implementation

Xiongfei Wang
Revolutionizing Energy Systems with Power Electronics
Power-electronic-based power systems

- Less physics-governed but more control-dependent dynamics
- Wide-timescale interactions bring more stability problems
- Vendor-specific black-box inverter control & protection
- Large-scale power-to-X plants ride through grid disturbances
- Evolving grid structure with challenges and opportunities
Grid-Forming Capability Requirements

Grid code, report, white paper

Grid-Forming Technology
Bulk Power System Reliability Considerations

Nov. 2021

Application of Advanced Grid-scale Inverters in the NEM
August 2021
White Paper
An Engineering Framework report on design capabilities needed for the future National Electricity Market

3333 Peachtree Road NE
Suite 600, North Tower
Atlanta, GA 30326
404-446-2560 | www.nerc.com

KTH - Grid-Forming - Xiongfei Wang
14-02-2023
Grid-Forming Capability Requirements
From European Network of TSOs (ENTSO-E)

Ideal resource to power system

- **Creating (form) system voltage**
- Contributing to fault level (short-circuit power)
- Contributing to total system inertia
- Support system survival to enable the effective operation of low frequency demand disconnection for rare system splits
- Acting as a sink to counter harmonics and inter-harmonics in system voltage
- Acting as a sink to counter any unbalance in system voltage
- Prevent adverse control system interactions

Grid-Forming Capability Requirements
From NERC

Essential requirement: internal voltage source

- Maintaining an internal voltage phasor:
  - Being constant or nearly constant in the sub-transient to transient time frame
  - Maintain synchronism with other devices
  - Regulate active and reactive power appropriately

- Islanding operation
- Arresting the decline or increase of frequency, and contributing the subsequent recovery of frequency
- Reactive power support and voltage regulation, aiding fast and stable post-fault voltage recovery
- Reduce adverse control interactions
- Providing the prescribed level of oscillation damping
- Active low-order harmonic cancellation
- Black-start capability

Grid-Forming Converter Technology
Synchronization is the foundation of ac systems

Electromechanical (swing) equation
\[ J \ddot{\omega}_m + D \dot{\omega}_m = \tau_m - \tau_e \]

Grid-Forming Converter Technology

Two fundamental synchronization principles

\[ \omega_c = \omega_g \]

\[ \omega_c \]

\[ \omega_g \]

Voltage-based synchronization

Power-based synchronization

Grid-Forming Converter Technology
Basics of power-based synchronization control

**Power-based synchronization**

\[ V_{mref} e^{j\theta_p} \]

\[ V_p \]

\[ V_g \]

\[ Z_g \]

\[ i \]

**Power-\omega controller options**

- **P**: Droop Control & Power Synchronization Control
- **Low-pass filter** (swing equation): Inertia and damping provision, yet with limited \( P-f \) droop gain
- **PI**: Zero static error under grid frequency deviation, inertia and damping, yet no \( P-f \) droop characteristic
- **Lead-lag filter**: flexible \( P-f \) droop gain, inertia and damping coefficients

**Active power-frequency droop control**

\[ P_{ref} \]

\[ P \]

\[ K_p \]

\[ \omega_e \]

\[ \omega_1 \]

\[ \frac{1}{s} \]

\[ \theta_p \]
Grid-Forming Converter Technology
Basics of power-based synchronization control

1. Power Sharing

2. Load frequency control

Grid-Forming Converter Technology

Need of current control with Grid-Forming?

- Low-frequency resonance and non-minimum phase
- Full control of current (harmonics, fault, etc.)

Instability and dynamic couplings in low SCR grids
Less control interactions in the high-frequency range

Grid-Forming Control

Grid-Following Control
Grid-Forming Converter Technology
Historical review of grid-forming control

Virtual synchronous generator (VSYNC) 2008
Virtual synchronous machine (VISMA) 2007
Droop control 1993
Load-frequency control 1986

Power synchronization control 2011
Synchronverter 2011
Synchronous machine matching control 2016
Virtual oscillator control 2016

Grid-Forming Converter Technology
Many control options yet grid code not ready yet

Grid-Forming Converter Technology
Many control options yet grid code not ready yet

Large-Disturbance Withstand Capability
Transient stability of grid-forming converter

Virtual Synchronous Machine (VSM) – swing dynamics

\[ P_{\text{ref}} - P_e - D\dot{\delta} = 2H\ddot{\delta} \]

Stable equilibrium point (SEP) \( c \)
Unstable equilibrium point (UEP) \( e \)

- Before SEP \( c \), \( P_m > P_e \), \( \omega_{VSM} \) increases
- After SEP \( c \), \( P_m < P_e \), \( \omega_{VSM} \) decreases
- Loss of synchronization (LOS) if \( \omega_{VSM} > \omega_g \) at UEP \( e \)

Critical clearing angle (CCA)
Critical clearing time (CCT)

- LOS if fault clearing time > CCT
Large-Disturbance Withstand Capability
Transient stability of grid-forming converters

Inertia-less droop control

\[ \dot{\delta} = K_i \left( P_{\text{ref}} - P_e \right) \]

- Converge to SEP c without overshoot
- Inertia-less control better than VSM

- Constant critical clearing angle (CCA)
  fixed to UEP e \( CCA = \delta_u \)
Large-Disturbance Withstand Capability
Transient stability of grid-forming converters

Inertia-less droop control

\[ \dot{\delta} = K_i \left( P_{\text{ref}} - P_e \right) \]

- Resynchronization capability
- More resilient against delayed fault clearance

## Large-Disturbance Withstand Capability
Inertia is not always good nor needed

### Post-disturbance

<table>
<thead>
<tr>
<th>With Equilibria</th>
<th>First-order $P$-$\omega$ (droop) control</th>
<th>Second-order $P$-$\omega$ (VSM) control</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
<td><img src="image3" alt="Diagram" /></td>
</tr>
</tbody>
</table>

- **Overdamped response**
- **Around one cycle of oscillation**
- **Re-synchronization**

### No Equilibria (FCT>CCT)

| ![Diagram](image4) | ![Diagram](image5) |

- **fault**
- **fault cleared**

---

14-02-2023

KTH - Grid-Forming - Xiongfei Wang
Large-Disturbance Withstand Capability
Current limiting control affects transient stability

Voltage control mode

\[ P_e = \frac{3V_{PCC}V_g}{2X_g} \sin \delta \]

Current limiting mode

\[ P_e = \frac{3}{2} I_{\text{max}} V_g \cos(\delta - \phi) \]

Small-Signal Stability Robustness
Breaking the limit of short-circuit ratio (SCR)

Flexibly configurable voltage and current sources
- Hybrid power- and voltage-based synchronization
- Dual-loop voltage and current control
- Voltage controller: virtual admittance or PI
- Voltage-based sync. as damper
- Asymmetrical virtual admittance for active damping
- Current control as damper
- High stability robustness with no SCR limit


Small-Signal Stability Robustness
Breaking the limit of short-circuit ratio (SCR)

Enhanced Grid-Forming control with active susceptance (AS)
- Using power synchronization control only
- AS for voltage-oriented vector control and enhanced damping

Grid-Forming STATCOM for Wind Power Plants
Interaction analysis and small-signal stability enhancement

Grid-Forming STATCOM

Comparison of PCC voltage mag. (WT-PLL bandwidth increases)

Comparison of active power (Power reference step responses)

Static synchronous compensator (STATCOM)
Grid-Following (GFL) or Grid-Forming (GFM)?

- Case I – GFL-WPP
- Case II – GFL-WPP + GFL-STATCOM
- Case III – GFL-WPP + GFM-STATCOM
- Which case is the most robust under small disturbance
