Improved Control Strategy of Grid-Forming Inverters for Fault Ride-Through in a Microgrid System

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Grid-forming (GFM) inverter fault ride-through (FRT) control is not yet fully studied.

- Affects system stability, especially in islanded microgrids
- Mostly study balanced faults or switch to current control for FRT capability
- No unified control structure for GFM inverters with GFM capabilities in grid-connected and islanded mode.

GFM inverter FRT control needs to be differentiated between grid-connected and islanded mode in microgrids:

- Grid-connected: Complies with IEEE 1547-2018
- Islanded: No standard yet.
CONTROL STRUCTURE OF GFM INVERTERS

- The same control structure is used for both grid-connected and islanded mode. (An integrator is enabled if it is in grid-connected mode for power tracking.)
- Separate FRT strategy: IEEE 1547-2018 compliant in grid-connected mode and designated FRT control in islanded mode.
GFM Inverter’s Behavior Under Fault Conditions

- Thevenin equivalent circuit of asymmetrical faults

![Thevenin equivalent circuit](image)

- Inverter behavior with asymmetrical faults

<table>
<thead>
<tr>
<th>Element</th>
<th>Positive Sequence</th>
<th>Negative Sequence</th>
<th>Zero Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_d$</td>
<td>$V_1$</td>
<td>$V_2\cos(2\omega t)$</td>
<td>0</td>
</tr>
<tr>
<td>$V_q$</td>
<td>0</td>
<td>$V_2\sin(2\omega t)$</td>
<td>0</td>
</tr>
<tr>
<td>$V_o$</td>
<td>0</td>
<td>0</td>
<td>$V_0\sin(\omega t)$</td>
</tr>
</tbody>
</table>
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GFM INVERTER’S BEHAVIOR UNDER FAULT CONDITIONS

- Initial study of GFM inverters under asymmetrical faults with different fault impedances:
  - With high impedance, the system is stable, but the tracking performance is very poor because the d-q components contain the negative-sequence components.
  - With low impedance, the system is unstable.

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2LG fault with 600-Ω fault impedance

2LG fault with 50-Ω fault impedance
Improved Control Strategy of GFM Inverter for FRT

- Dual control structure of the improved control strategy of GFM inverters:
  - Control objective: Achieve balanced and stable three-phase voltages under asymmetrical faults.
  - Extract the positive- and negative-sequence accurately and control them separately.
**Improved Control Strategy of GFM Inverter for FRT**

- **Virtual impedance control:**
  - Need virtual impedance control to reduce the voltage reference because the fault generates a large fault current and causes the voltage to drop.
  - Only the d-component of the positive sequence is needed.

\[
V_{od}^+ = V_{od}^+ - (Ri_{od}^+ - Xi_{oq}^+), V_{oq}^+ = 0, V_{od}^- = 0, V_{oq}^- = 0
\]

- **Adaptive virtual impedance control**

<table>
<thead>
<tr>
<th>Tracking error ( e = V_{od}^{+*} - V_{od}^{+} )</th>
<th>( V_{od}^{+*} )</th>
<th>( R )</th>
<th>( X )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( &gt; 5 \text{ V} )</td>
<td>Be reduced.</td>
<td>If ( i_{od}^+ ) is positive, increase ( R ) by ( \frac{0.8e}{i_{od}^+} ), otherwise reduce ( R ) by ( \frac{0.8e}{i_{od}^+} ).</td>
<td>If ( i_{oq}^+ ) is positive, reduce ( X ) by ( \frac{0.2e}{i_{oq}^+} ), otherwise increase ( X ) by ( \frac{0.2e}{i_{oq}^+} ).</td>
</tr>
<tr>
<td>( &lt; -5 \text{ V} )</td>
<td>Be increased.</td>
<td>If ( i_{od}^+ ) is positive, reduce ( R ) by ( \frac{0.8e}{i_{od}^+} ), otherwise increase ( R ) by ( \frac{0.8e}{i_{od}^+} ).</td>
<td>If ( i_{oq}^+ ) is positive, increase ( X ) by ( \frac{0.2e}{i_{oq}^+} ), otherwise reduce ( X ) by ( \frac{0.2e}{i_{oq}^+} ).</td>
</tr>
</tbody>
</table>

Even though this is a small change, its improvement to the stability of GFM inverters is significant.
SIMULATION RESULTS

- Islanded microgrid with 2LG fault with 50-ohm fault impedance (with only negative-sequence control)

- The GFM inverter has a problem to track the target control references.
- Without virtual impedance control, the GFM inverter is unstable with the studied fault.
**Simulation Results**

- Islanded microgrid with 2LG fault with 50-ohm fault impedance (with negative-sequence and virtual impedance control)

- Virtual impedance control can effectively generate the correct and reachable voltage reference.
- The tracking performance of the GFM inverter significantly improves and so does the stability.
SIMULATION RESULTS

- Islanded microgrid with LG fault with 0.1-ohm fault impedance

- Adaptive virtual impedance control functions well to further reduce the tracking error.
- The stability of the GFM inverter is further improved.
**SIMULATION RESULTS**

- Islanded microgrid with high- and low-impedance faults

<table>
<thead>
<tr>
<th>Fault</th>
<th>Virtual Impedance</th>
</tr>
</thead>
<tbody>
<tr>
<td>LG, 0.1 ohm</td>
<td>R_VI=0.065; L_VI=1.4e-3</td>
</tr>
<tr>
<td>LG, 100 ohms</td>
<td>R_VI=0.065; L_VI=1.4e-3</td>
</tr>
<tr>
<td>LLG, 0.1 ohm</td>
<td>R_VI=0.025; L_VI=1.43e-3</td>
</tr>
<tr>
<td>LLG, 50 ohms</td>
<td>R_VI=0.025; L_VI=1.4e-3</td>
</tr>
<tr>
<td>LL, 0.1 ohm</td>
<td>R_VI=0.025; L_VI=1.4e-3</td>
</tr>
<tr>
<td>LL, 100 ohms</td>
<td>R_VI=0.025; L_VI=1.4e-3</td>
</tr>
<tr>
<td>3LG, 1 ohm</td>
<td>R_VI=0.025; L_VI=1.4e-3</td>
</tr>
<tr>
<td>3LG, 100 ohms</td>
<td>R_VI=0.0138; L_VI=0.77e-3</td>
</tr>
</tbody>
</table>

The proposed control for FRT capability works well for all the high- and low-impedance faults, balanced and unbalanced faults.
SIMULATION RESULTS

- Grid-connected microgrid with LG fault with 0.1-ohm fault impedance

- Inverter trips after 2 seconds because the PCC voltage stays lower than 0.5 p.u. for 2 seconds (momentary cessation)
- Only generates power for the first five cycles and then goes to zero injection.
CONCLUSION

- Negative-sequence control with virtual impedance control is essential to make the GFM inverter with FRT capability for islanded microgrids.

- Virtual impedance control can be very simple and effective with only the d-component of the positive-sequence control.

- Virtual impedance control needs to be adaptive to cope with different voltage drops caused by various unbalanced faults.

- The GFM inverter can be IEEE 1547-2018 compliant in grid-connected mode and designed with FRT capability in islanded mode.
Thank You

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This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. This work was supported by the Laboratory Directed Research and Development (LDRD) Program at NREL. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.