Effectively interconnecting high-level penetration of photovoltaic (PV) systems requires careful technical attention to ensuring compatibility with electric power systems. Standards, codes, and implementation have been cited as major impediments to widespread use of PV within electric power systems.

On May 20, 2010, in Denver, Colorado, the National Renewable Energy Laboratory, in conjunction with the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE), held a workshop to examine the key technical issues and barriers associated with high PV penetration levels with an emphasis on codes and standards.

There was significant focus on future inverters that would be capable of staying online during grid anomalies while maintaining grid safety and reliability. Discussions included multiple definitions of high penetration, enhanced monitoring and control opportunities, and the new IEEE P1547.8 (Expanded Use of High PV Penetration Levels) that will focus on resolution of many concerns of high-penetration PV deployment.

DEFINING HIGH PENETRATION

- **Minimum Load to Generation Ratio:** this is the annual minimum load on the relevant power system section divided by the aggregate DG capacity on the power system section
- **Stiffness Factor:** the available utility fault current divided by DG rated output current in the affected area
- **Fault Ratio Factor:** available utility fault current divided by DG fault contribution in the affected area
- **Ground Source Impedance Ratio:** ratio of zero sequence impedance of DG ground source relative to utility ground source impedance

<table>
<thead>
<tr>
<th>Type of Ratio</th>
<th>What is it useful for?</th>
<th>Suggested Penetration Level Ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Load to Generation Ratio</td>
<td>Ground fault overvoltage analysis less than 3 when DG is not effectively grounded</td>
<td>Very Low Penetration</td>
</tr>
<tr>
<td></td>
<td>Islanding analysis (see ratios 2/3 of those shown)</td>
<td>Low (no impact)</td>
</tr>
<tr>
<td>Fault Ratio Factor</td>
<td>Overcurrent device coordination</td>
<td>Very Low Penetration 10 to 5</td>
</tr>
<tr>
<td></td>
<td>Overcurrent device ratings</td>
<td>Moderate Penetration 6 to 3</td>
</tr>
<tr>
<td></td>
<td>&gt; 10 Inverters</td>
<td>Higher Penetration</td>
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<td>&gt; 6 Inverters</td>
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</tr>
<tr>
<td></td>
<td>&gt; 3 in inverters</td>
<td></td>
</tr>
<tr>
<td>Stiffness Factor</td>
<td>Voltage Regulation</td>
<td>&gt; 100</td>
</tr>
<tr>
<td></td>
<td>Voltage is a good indicator of voltage influence. Wind/PV have higher ratios due to their fluctuations. Breaks the ratio. Use to check for current reversal at upstream regulator devices</td>
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</tr>
<tr>
<td></td>
<td>&gt; 50</td>
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<td></td>
<td>&gt; 25</td>
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<td>&gt; 20</td>
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<tr>
<td>Ground Source Impedance Ratio</td>
<td>Ground fault deinsertion</td>
<td>&gt; 100</td>
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<td>&gt; 100</td>
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<td>&gt; 10</td>
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</tbody>
</table>

GRID-INTEGRATED SMART INVERTERS

- Connect/Disconnect from Grid
- Output Power Management
- Intelligent Volt-Var Control
- Storage Management
- Event/History Logging
- Status Reporting/Reading
- Time-sync

DYNAMIC CONTROL OF INVERTERS

**TECHNICAL CHALLENGES**

- Most of the changes can be done in software
- Minor hardware changes
- Additional Sensors
- UPS for LVRT
- Minimal additional cost
- Inverter will operate at higher current levels when off of unity power factor than at unity
- Impacts efficiency and reliability

**DYNAMIC CONTROL**

- Communications to PV inverters to control operational setpoints
  - Real Power Limit
  - Curtail production?
  - Ramp rates
  - Reactive Power Level
  - VARs
  - Power Factor
  - Voltage control
  - Trip levels
  - Over/Under Voltage
  - Over/Under Frequency
  - Operate like traditional power plants

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NREL is a national laboratory of the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy. Operated by the Alliance for Sustainable Energy, LLC.

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