Evaluation of Potential Methods for Large Scale Inverter Commissioning Sag Testing

EPRI Power Quality Research Project Discussion

Session 6 – Grid Simulators for Models and Standards Validation:
6th International Workshop on Grid Simulator Testing of Wind Turbine Power Trains and Other Renewable Technologies

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EPRI and Power Quality

Key Issues Driving Program 1’s Research

- Proactive PQ
- Getting maximum value from PQ data streams
- Coping with Increased Grid Complexity
- Improving Customer Service and Satisfaction
2022 Power Quality Project Set 1C: Achieving Cost-Effective Edge-of-Grid PQ Compatibility

Summary of 2022 Projects and Deliverables

P001.007: System Compatibility Research

- **Objective:** Characterize the PQ issues surrounding dual-function circuit breakers (Project 1) and evaluate a series injection mitigation technology (Project 2).
- **Description:**
  - Project 1: The 2014 National Electrical Code (NEC®) requires both Arc Fault and Ground Fault protection on kitchen and laundry circuits and AFCI breakers in the entire home. Specifically, the AF/GFCI breakers have been shown to trip during power quality events. This project will seek to understand the mechanisms and solutions.
  - Project 2: This project aims to conduct an array of PQ tests to better understand and quantify the series injection mitigation technology known as the Sag Fighter. This is a continuation of a previous effort where the results were not conclusive.
- **Deliverable(s):**
  - Evaluation of Dual Function Circuit Breakers against PQ Issues *(Technical Report)*
  - Technology Assessment and Application Guide for the Sag Fighter *(Technical Report)*

P001.008: PQ Impact Assessment and Sensitivity of Grid-Connected Loads and DER

- **Objective:** Determine the feasibility of large-scale DER inverter voltage sag testing
- **Description:**

Large-scale Inverter-connected systems: Understanding and solving the voltage sag performance problem

- **Deliverable(s):** Potential Methods for Large Scale Inverter Commissioning Sag Testing *(Technical Report)*

P001.009: Strategies and Tools for Edge-of-Grid PQ Detection and Analysis

- **Objective:** Develop EPRI Handbook for Conducting Power Quality Assessments.
- **Description:** Utility PQ engineers need resources to understand how to conduct all types of PQ Investigations. The project aims to develop a clear step-by-step handbook to document steps for conducting PQ Assessments for a myriad of PQ Issues (Sags, Grounding, Surge, Harmonics, Radiated Emissions, etc.). This work will be used in future EPRI training programs as well as in development of future PQ Investigator algorithms.
- **Deliverable(s):** EPRI PQ Assessment Handbook Version 1.0 *(Technical Report)*
Project Objective: Determine the feasibility of large-scale DER inverter voltage sag testing

Description: Field verification of the voltage sag settings and response large-scale PV inverters during commissioning is not easily accomplished, therefore not required.

This project seeks to research feasible approaches for verification using field simulation tools and/or large voltage sag generators.

Deliverable(s): Potential Methods for Large Scale Inverter Commissioning Sag Testing (Technical Report)
Why Test at Commissioning?
Case Studies for Utility Scale Solar Facility Performance and Power Quality Issues

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2022 Georgia Tech Fault & Disturbance Analysis Conference
TVA Case Study: Sudden Solar Plant MW Reduction Due to Transmission System Fault and Related Voltage Sag

What if this occurs in 2040 when > 27% of Generation will be solar in TVA’s Territory?
On-Site Participants Left to Right:
Mark Stephens (EPRI), Scott Bunton (EPRI), Meredyth Crichton (Clemson, Executive Director, Dominion Energy Innovation Center), Joe Hodges (DESC), Joey Jeffcoat (DESC), Jeff Inabinet (DESC), Jonathan Sides (TVA), Christopher Burge (TVA), David Deloach (TVA), Russel Moore (Clemson), Moazzam Nazir (Clemson). Participant Not Shown: Dusty Rhoad (Clemson)

Virtual Participants in WebEx Only:
Gokhan Ozkan (Clemson, eGrid Lead Researcher), Tom Key (EPRI), Curtiss Fox (EPRI), Yiwei Ma (EPRI), Naema Blankenship (AEP), Chuck Brewster (EPRI), Michael Whaley (Powerco), Robin Pittwood (Powerco), Matthew Edwards (SRP), James Rossman (TVA), Adelina Mejia-Zelaya (ComEd)
Recent NERC Reports
Recent Related NERC Reports

**Odessa Disturbance**
Texas Events: May 9, 2021 and June 26, 2021
Joint NERC and Texas RE Staff Report
September 2021

**Multiple Solar PV Disturbances in CAISO**
Disturbances between June and August 2021
Joint NERC and WECC Staff Report
April 2022

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# Recent Disturbance Reports

## Table ES.1: Overview of Disturbances

<table>
<thead>
<tr>
<th>Disturbance and Name</th>
<th>Initiating Fault Event</th>
<th>Description of Resource Loss*</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 24, 2021 “Victorville”</td>
<td>Phase-to-Phase Fault on 500 kV Line</td>
<td>Loss of 765 MW of solar PV resources (27 facilities)</td>
</tr>
<tr>
<td>July 4, 2021 “Tumbleweed”</td>
<td>Phase-to-Phase Fault on 500 kV Line</td>
<td>Loss of 605 MW of solar PV resources (33 facilities)</td>
</tr>
<tr>
<td>August 25, 2021 “Lytle Creek Fire”</td>
<td>Phase-to-Phase Fault on 500 kV Line</td>
<td>Loss of 583 MW of solar PV resources (30 facilities)</td>
</tr>
</tbody>
</table>

* All events occurred in afternoon (12:00 and 4:00 p.m. Pacific)

Ref: Multiple Solar PV Disturbances in CAISO Disturbances between June and August 202, Joint NERC and WECC Staff Report, April 2022
Table 2.1: Causes of Reduction

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow Active Power Recovery</td>
<td>111</td>
<td>193</td>
<td>184</td>
<td>91</td>
</tr>
<tr>
<td>Momentary Cessation</td>
<td>310</td>
<td>120</td>
<td>192</td>
<td>447</td>
</tr>
<tr>
<td>Cause Unknown</td>
<td>103</td>
<td>103</td>
<td>112</td>
<td>24</td>
</tr>
<tr>
<td>Inverter DC Voltage Unbalance</td>
<td>-</td>
<td>77</td>
<td>15</td>
<td>4</td>
</tr>
<tr>
<td>Inverter AC Overcurrent</td>
<td>49</td>
<td>74</td>
<td>17</td>
<td>13</td>
</tr>
<tr>
<td>Inverter DC Overcurrent</td>
<td>98</td>
<td>9</td>
<td>47</td>
<td>3</td>
</tr>
<tr>
<td>Inverter UPS Failure</td>
<td>-</td>
<td>4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Inverter Overfrequency</td>
<td>-</td>
<td>-</td>
<td>43</td>
<td>18</td>
</tr>
<tr>
<td>Inverter Underfrequency</td>
<td>14</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Inverter AC Undervoltage</td>
<td>100</td>
<td>-</td>
<td>16</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>785</td>
<td>566</td>
<td>626</td>
<td>600</td>
</tr>
</tbody>
</table>

Figure 2.1: June 24 Disturbance Causes of Solar PV Reduction

Figure 2.2: July 4 Disturbance Causes of Solar PV Reduction

Figure 2.3: July 28 Disturbance Causes of Solar PV Reduction

Figure 2.4: August 25 Disturbance Causes of Solar PV Reduction

Ref: Multiple Solar PV Disturbances in CAISO Disturbances between June and August 202, Joint NERC and WECC Staff Report, April 2022
## Odessa Report

**Table 1.1: Causes of Reduction**

<table>
<thead>
<tr>
<th>Cause of Reduction</th>
<th>Reduction [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLL Loss of Synchronism</td>
<td>389</td>
</tr>
<tr>
<td>Inverter AC Overvoltage</td>
<td>269</td>
</tr>
<tr>
<td>Momentary Cessation</td>
<td>153</td>
</tr>
<tr>
<td>Feeder AC Overvoltage</td>
<td>147</td>
</tr>
<tr>
<td>Unknown</td>
<td>51</td>
</tr>
<tr>
<td>Inverter Underfrequency</td>
<td>48</td>
</tr>
<tr>
<td>Not Analyzed</td>
<td>34</td>
</tr>
<tr>
<td>Feeder Underfrequency</td>
<td>21</td>
</tr>
</tbody>
</table>

Ref: Odessa Disturbance Texas Events: May 9, 2021 and June 26, 2021 Joint NERC and Texas RE Staff Report September 2021
There is presently no NERC Reliability Standard that obligates or that gives appropriate authority for Reliability Coordinators (RCs), TOPs, or Balancing Authorities (BAs) to assess the performance of an interconnected facility, identify abnormalities, and execute corrective actions to eliminate this abnormal performance.

In most cases, the systemic underlying issue is that performance requirements are not established or are not clear.

The lack of performance validation (validating that the facility is performing as expected) leads to these large-scale and widespread events with many affected facilities rather than addressing underlying systemic issues before they become larger events.

RCs, TOPs, and BAs should be performing performance assessments and validation for their generation fleet, identifying any unreliable operation of connected resources, and addressing those issues in a timely manner.
What do Standards Say?
Relevant Standards: IEEE 1547-2018 Field Test Requirements

- Neither High / Low-Voltage Ride-Through test is not part of commissioning (NR).

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Compliance at PCC achieved by:</th>
<th>Type tests</th>
<th>DER evaluation</th>
<th>Commissioning tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.4 Voltage</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.4.1 Manditory voltage tripping requirements</td>
<td>DER System</td>
<td>R</td>
<td>Design: R, Installation: R²</td>
<td>D</td>
</tr>
<tr>
<td></td>
<td>Composite</td>
<td>L</td>
<td>Design: R, Installation: R²</td>
<td>D</td>
</tr>
<tr>
<td>6.4.2.1 General requirements and exceptions</td>
<td>DER System</td>
<td>R</td>
<td>R</td>
<td>D</td>
</tr>
<tr>
<td></td>
<td>Composite</td>
<td>L</td>
<td>R</td>
<td>D²</td>
</tr>
<tr>
<td>6.4.2.2 Voltage disturbances within continuous operation region</td>
<td>DER System</td>
<td>R</td>
<td>Design: R, Installation: R²</td>
<td>D</td>
</tr>
<tr>
<td></td>
<td>Composite</td>
<td>L</td>
<td>R</td>
<td>D²</td>
</tr>
</tbody>
</table>

**Table 43**—Interconnection test specifications and requirements for DER that shall meet requirements at the PCC

<table>
<thead>
<tr>
<th>LEGEND</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>DER system</td>
<td>DER system is fully compliant at PCC*—no supplemental DER device needed</td>
</tr>
<tr>
<td>*Individual DER units that are considered fully compliant at the PCC may only be considered fully compliant at the PCC if the impedance between the PoC and the PCC is less than 0.5% on the DER rated apparent power and voltage base.</td>
<td></td>
</tr>
<tr>
<td>Composite</td>
<td>Composite of partially compliant DER that is, as a whole, fully compliant at PCC*—may need one or more supplemental DER device(s).</td>
</tr>
<tr>
<td>*Individual DER units that are considered fully compliant at the PoC shall not be considered fully compliant at the PCC if the impedance between the PoC and the PCC is equal to or greater than 0.5% on the DER rated apparent power and voltage base.</td>
<td></td>
</tr>
<tr>
<td>NR</td>
<td>Not Required</td>
</tr>
<tr>
<td>R</td>
<td>Required</td>
</tr>
<tr>
<td>L</td>
<td>Limited type testing is limited to partial compliance of the individual DER unit or DER system in order to evaluate the DER unit or DER system performance characteristics for later use in the DER evaluation that verifies full compliance of the composite DER at the PCC. The DER unit or DER system may not have any compliance at all with certain requirements, leaving on the supplemental equipment to comply.</td>
</tr>
<tr>
<td>D</td>
<td>Dependent on DER Design Evaluation</td>
</tr>
<tr>
<td>NA</td>
<td>Not Applicable</td>
</tr>
</tbody>
</table>

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sbtnote@epri.com

*Align trip settings at DER devices and substation; |
| Verify correct installation settings.
Voltage Disturbance Ride-through Requirements (Clause 7.2.2)

<table>
<thead>
<tr>
<th>Applicable RPA</th>
<th>IBR Unit-level Tests</th>
<th>IBR Plant-level Verifications at the RPA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test Types</td>
<td>Design Evaluation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Evaluation—As-built Installation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tests—Commissioning</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Validation—Post-Commissioning Model</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Monitoring—Post-Commissioning</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Testing—Periodic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Verification—Periodic</td>
</tr>
<tr>
<td>Entity Responsible</td>
<td>Device Manufacturer / IBR Unit / Supplemental IBR</td>
<td></td>
</tr>
<tr>
<td>POC* &amp; POM **</td>
<td>TS Operator/TS Owner / IBR Developer</td>
<td>TS Operator/TS Owner / IBR Developer</td>
</tr>
<tr>
<td></td>
<td>TS Operator/TS Owner / IBR Developer</td>
<td>TS Operator/TS Owner / IBR Developer</td>
</tr>
<tr>
<td></td>
<td>TS Operator/TS Owner / IBR Operator</td>
<td>TS Operator/TS Owner / IBR Developer</td>
</tr>
<tr>
<td></td>
<td>TS Operator/TS Owner / IBR Developer</td>
<td>TS Operator/TS Owner / IBR Developer</td>
</tr>
</tbody>
</table>

Clause 7 Response to TS Abnormal Conditions

R = Required
NR = Not Required
D = Directive

*See requirements in clause 7.2.2.3
** See requirements in clause 7.2.2.1, 7.2.2.2, 7.2.2.4, and 7.2.2.6

Ref: IEEE 2800-2022 Standard for Interconnection and Interoperability of Inverter-Based Resources Interconnecting with Associated Transmission Systems
IEEE 2800/P2800.2 Test and Verification Framework Requires Models

What's the requirement?

Where's the reference point of applicability (RPA)?

Required path to verification

Category of test and verification needed

Plant-Level Modeling

Ride-Through

Type tests (units)

IBR evaluation (Design & As-Built)

Commissioning Test

Post-commissioning model validation

Post-commissioning monitoring

Periodic test or verification

Plant-Level Testing

Requirement

Path to verification

Voltage Control
How Could Testing be Done?
Test Equipment ? Common Sag Generator Types

- The **transformer-switch** type uses some form of switching to switch from nominal to reduced voltage for the testing.
  - Most such voltage-sag generators use electronic switches employing either an insulated gate bipolar transistor (IGBT), or a silicon-controlled rectifier (SCR).
  - Units up to 1000A per phase are currently commercially available.

- The **amplifier** type and includes a controller, a waveform generator, a data-acquisition system, and a power-amplification section.
  - This waveform generator can simulate any point-on-wave and provide varying magnitude, duration, frequency, and harmonics, thereby allowing a user more precise control of the voltage-sag characteristics.
  - The amplifier sag generator typically employs multiple power conversions—requiring transformer isolation.

- A third form of sag generator is commonly referred to as the **impedance divider** type, which uses a thyristor-controlled reactor to switch impedances for creating voltage sags.
  - Generally, the impedance-divider sag generator weighs less than the other types of sag generators and provides maximum power.
  - May have limited available sag depth adjustments.
EPRI: Pioneered Transformer-Switch Type

Sag Types Per IEEE 1668

- Type I
- Type II
- Type II A.1
- Type II A.2
- Type III

200A EPRI Tri-Mode Porto-Sag
Transformer-Switch Type Sag Generators

- The transformer type uses some form of switching to switch from nominal to reduced voltage for the testing.
- Contactors can be used, but typically cannot provide precise switching nor can they allow phase-angle control of sags.
- Most such voltage-sag generators use electronic switches employing either an insulated gate bipolar transistor (IGBT), or a silicon-controlled rectifier (SCR).
- Units up to 200A per phase are currently commercially available with larger ones (600A and 1000A) pending.
- **EPRI Experience with Testing Smaller IBRs with Transformer-Switch Type: Continually Blew Snubber Circuits in the Generator.**
  - Switched to Amplifier Based Systems for IBR
Approaches

Large Transformer-Switch Type Voltage Sag Generator

Impedance Divider

Example: Voltage Dip

Voltage Manipulation Only

Amplifier/Grid Simulator Based Systems

Would need to be Mobile

Voltage & Frequency Manipulation
DOMINION ENERGY INNOVATION eGrid

Harmonic Filter

15 MW HIL Grid Simulator Performance Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Specification Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Power</td>
<td>15000 kVA</td>
</tr>
<tr>
<td>Frequency range</td>
<td>45...65 Hz</td>
</tr>
<tr>
<td>Sequence capability</td>
<td>3 and 4 wire</td>
</tr>
<tr>
<td>High Voltage Ride Through HVRT</td>
<td>100...145%</td>
</tr>
<tr>
<td>Low Voltage Ride Through LVRT</td>
<td>100...0%</td>
</tr>
<tr>
<td>Unsymmetrical LVRT</td>
<td>yes</td>
</tr>
<tr>
<td>Power quality PQ evaluation</td>
<td>yes</td>
</tr>
</tbody>
</table>
Imagining The Mobile Test System
IEEE 2800 Transmission Connected IBR Options
Brainstorming Mobile Test System Components

Test Setup Medium Voltage Transformers (MVTs):
- May not need to be continuous power rated.
- Must have multiple Taps to Interface with different System Voltages

**Amplifier System:
- Must have a Grid-Friendly Active Front End.
- Must be rated for current and how long it can sustain current.
- Must be able to absorb current and not trip.

Approach: Test Plant Controller and 1 or 2 IBRs. Make sure other IBR units are set with the same parameters.

*Auxiliary Power Required: Could be 480V 30 Amp Generator (provide by system or locally rented) could provide Auxiliary Power for Amplifier Control Power, Fans, Cooling Pump, etc.
Should Fit within Standard Trailer Dimensions Weight Capacities.

Ref: Sag Specialized Transport, https://osagespecial.com
Questions to Consider

- Can we take “off-the-shelf” grid simulator hardware and “Trailerize”?  
- What is the optimal sized system for Mobile Testing?  
- Can system fit within Standard Tractor Trailer Weight and Size Dimensions?  
- Have any OEM/Vendor attempted this before?  
- What are the electrical SCR requirements for the test hardware?  
- Who would best “own” equipment and perform tests?  
- If successful, could this be part of future Commissioning Requirements?

Safety/Arc-Flash Considerations Must be incorporated.
Conclusions
Conclusions/Final Thoughts

- As NERC has noted the lack of performance validation (validating that the facility is performing as expected) leads to these large-scale and widespread events with many affected facilities rather than addressing underlying systemic issues before they become larger events.

- The best technology for mobile testing is to be determined.
  - Amplifier based systems offer the widest range of test capabilities (Voltage and Frequency)

- If done during commissioning, Mobile Field Testing of large-scale PV Installations should help improve the reliability of the evolving grid.

Collaboration Welcomed!