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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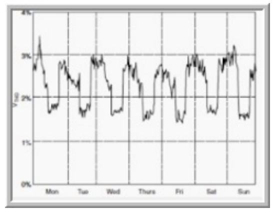
EPRI and Power Quality
Key Issues Driving Program 1's Research



- 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
- **Descript** ... ing commissioning is not easily ac ... simulation tools or large voltage

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)

EPRI Power Quality Research Program P001.008 2022 Project: Potential Methods for Large Scale Inverter Commissioning Sag Testing

- **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)

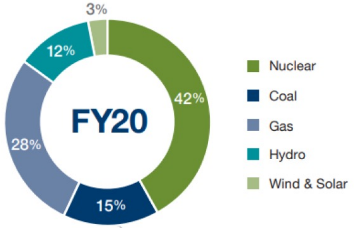
Why Test at Commissioning?

EPRI Research Funder: Concerns Raised by TVA

36,937 MW
Summer Net Capacity

Adding
7,000 to 10,000 MW of solar energy by 2040

Robust and Diverse Energy Portfolio*



Generating Assets
- 3 Nuclear Sites (7 Units)
- 5 Coal-Fired Sites (25 Units)
- 29 Hydroelectric Sites (109 Units)
- 1 Pumped-Storage Site (4 Units)
- 9 Combustion Turbine Gas Sites (86 Units)
- 8 Combined Cycle Gas Sites (14 Units)
- 1 Co-Generation Unit
- 14 Solar Energy Sites

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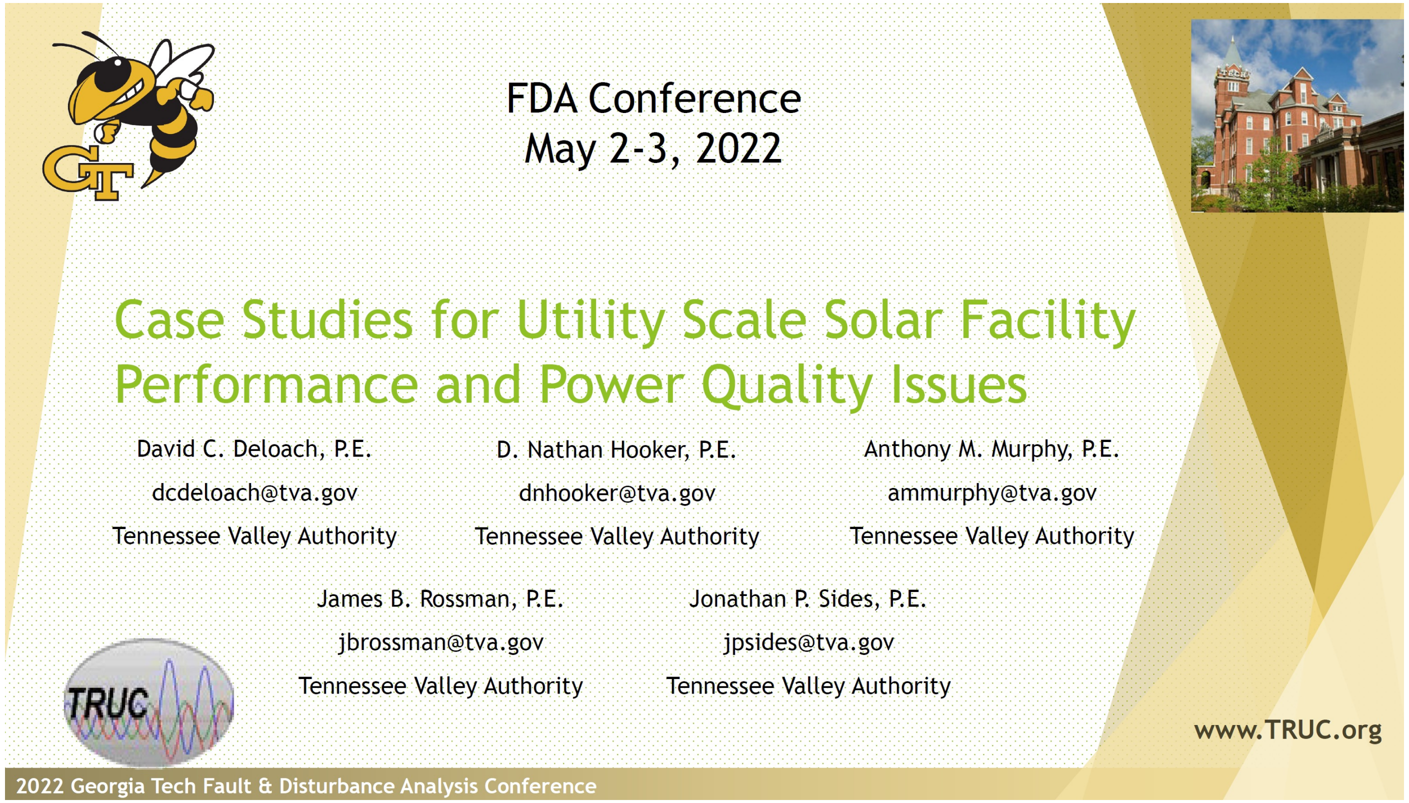
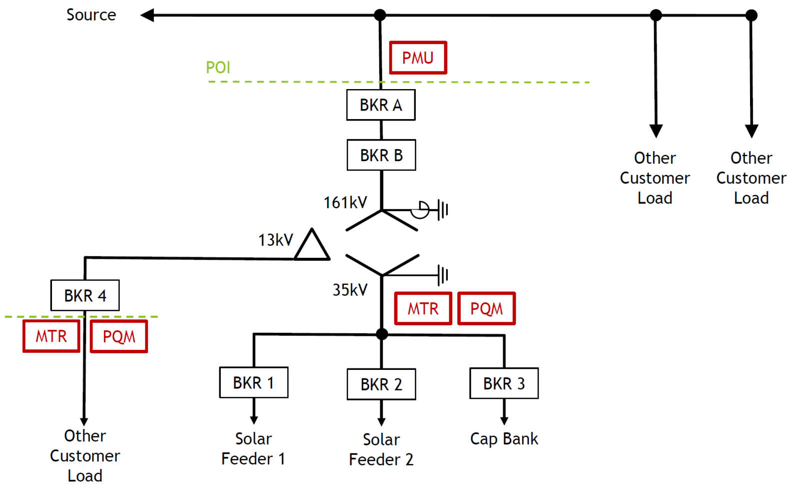


TVA Case Study: Sudden Solar Plant MW Reduction Due to Transmission System Fault and Related Voltage Sag

54MW, 161kV
Solar Plant

Served on a 161kV
Radial with 2 other
customer loads

Other Customer
Load Served from
Delta Tertiary



54MW, 161kV
Solar Plant

85%, 2.5cycle
Voltage Sag

43MW pre-event
18MW post-event
35MW after 12sec
40MW after 6.5min

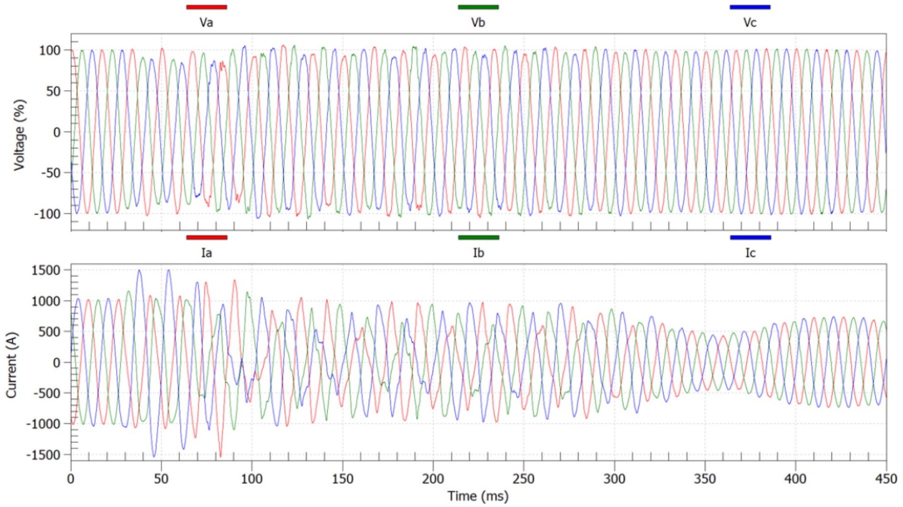
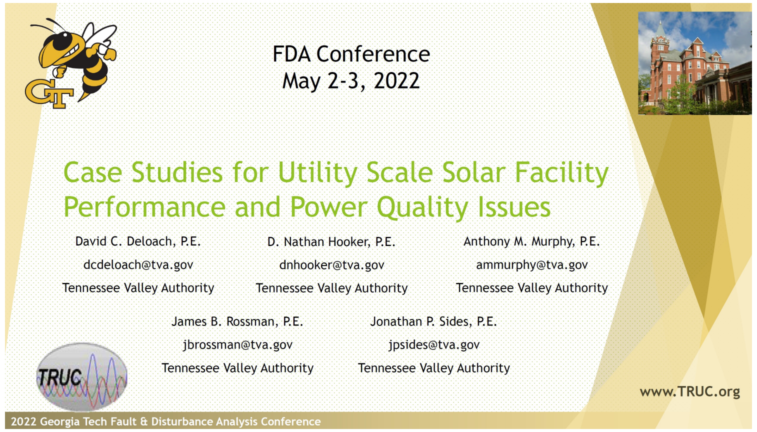


Fig. 5. Solar plant MW reduction associated with transmission system fault related voltage sag



36,937 MW
Summer Net Capacity

Adding
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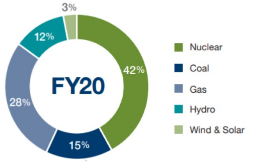

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- 3 Nuclear Sites (7 Units)
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- 8 Combined Cycle Gas Sites (14 Units)
- 1 Co-Generation Unit
- 14 Solar Energy Sites

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What if this occurs in 2040 when > 27% of Generation will be solar in TVA's Territory?

DOMINION ENERGY INNOVATION CENTER SITE VISIT (August 31, 2022)

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), Naeema Blankenship (AEP), Chuck Brewster (EPRI), Michael Whaley (Powerco), Robin Pittwood (Powerco), Matthew Edwards (SRP), James Rossman (TVA), Adelina Mejia-Zelaya (ComEd)

DOMINION ENERGY INNOVATION CENTER SITE VISIT: LARGE SCALE INVERTER TESTING

Location: 1240 Supply St, North Charleston, SC 29405

Date: August 31, 2022

Time: 9:00 AM- TBD

Facilitator: Meredyth Crichton
Executive Director,
Dominion Energy
Innovation Center

EPRI Meeting Goals:

1) To gain a better understanding of the capabilities of the Dominion Energy Innovation Center.
2) To learn about the challenges of large-scale inverter sag testing.
3) To Discuss mobile applications of testing technology.
4) Learn what the test center has done with others in this realm.
5) Involvement of EPRI Power Quality Research Funders (via WebEx or in person).

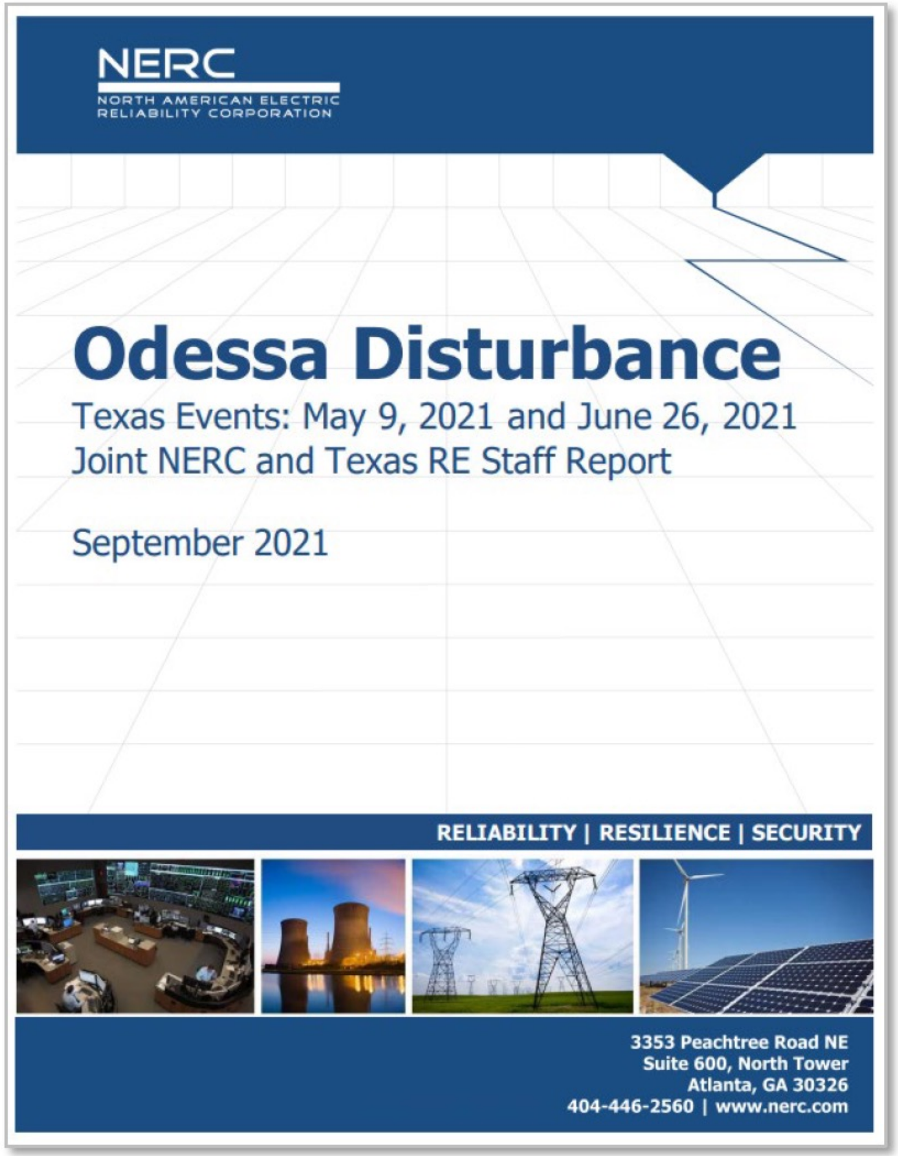
Meeting Format:

Site Tour and Discussions plus WebEx with Interested Program 1 EPRI Research Funders

Time	Item	Location
9:00-9:20	Introductions and Kick-Off	EIC Conference Room 101
9:30- 11:00	Laboratory Tour	Labs
11:30-12:30	Lunch	GEC Boardroom
1 PM to 3 PM	WebEx - Quick Intro: Discussion of EPRI's Research Project on Large Scale Inverter Testing - Experience and Considerations with Large Scale Inverter Testing (Curtis Fox, EPRI, TBD – Innovation Center) - Utility Discussion of Need for Capabilities - Dominion Energy Innovation Center Overview and Capabilities - Next Steps	GEC Boardroom
3:00-3:30	Concluding Discussions and Action Items	GEC Boardroom

Recent NERC Reports

Recent Related NERC Reports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Odessa Disturbance

Texas Events: May 9, 2021 and June 26, 2021
Joint NERC and Texas RE Staff Report

September 2021

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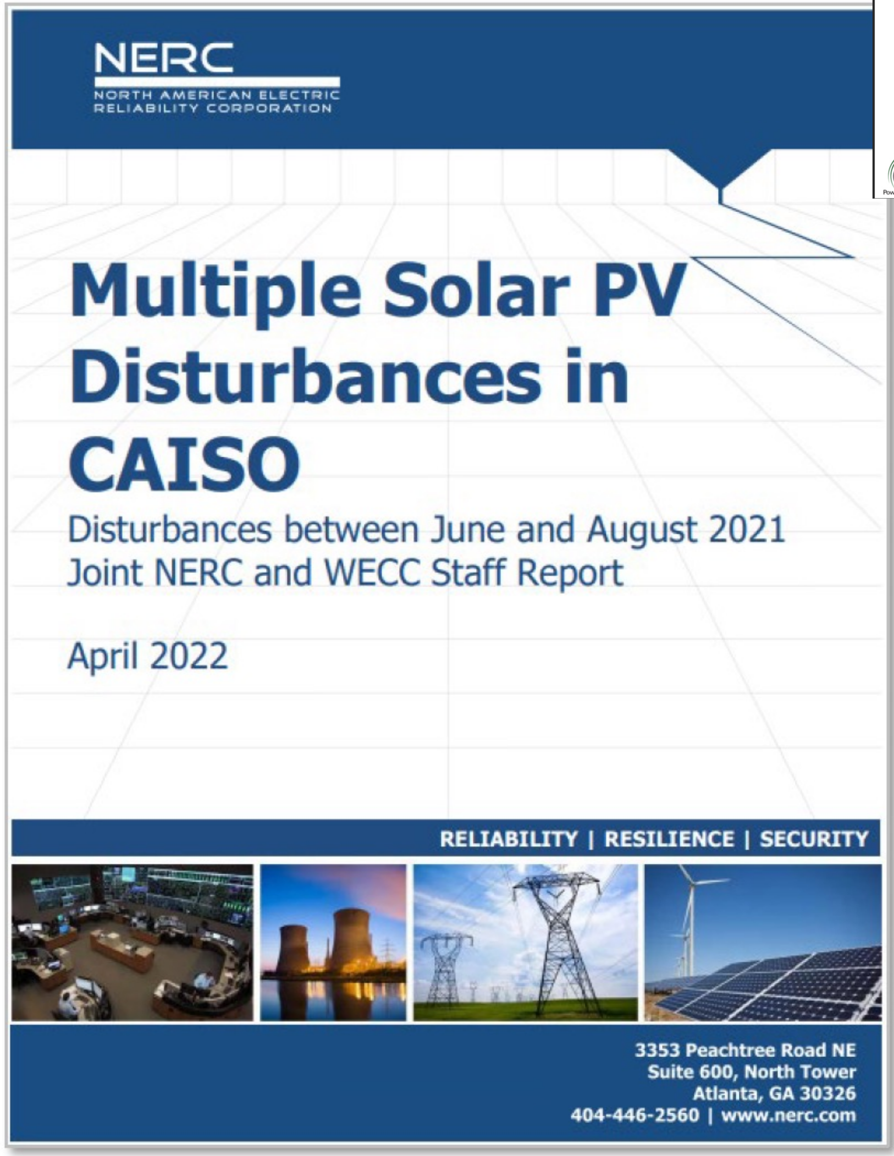
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Multiple Solar PV Disturbances in CAISO

Disturbances between June and August 2021
Joint NERC and WECC Staff Report

April 2022

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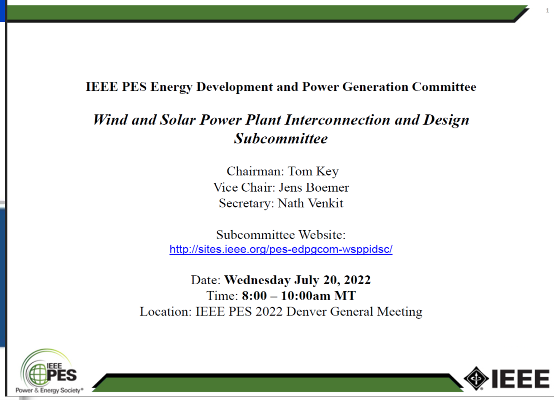

IEEE PES Energy Development and Power Generation Committee

Wind and Solar Power Plant Interconnection and Design Subcommittee

Chairman: Tom Key
Vice Chair: Jens Boemer
Secretary: Nath Venkit

Subcommittee Website:
http://sites.ieee.org/pes-edpgcom-wsppidsc/

Date: **Wednesday July 20, 2022**
Time: **8:00 – 10:00am MT**
Location: IEEE PES 2022 Denver General Meeting

Rich Bauer

Office (404) 446-9738

Cell (404) 357-9843

rich.bauer@nerc.net

Recent Disturbance Reports

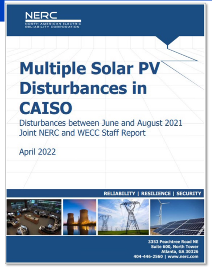


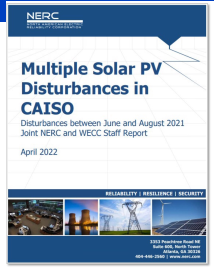
Table ES.1: Overview of Disturbances

Disturbance and Name	Initiating Fault Event	Description of Resource Loss*
June 24, 2021 "Victorville"	Phase-to-Phase Fault on 500 kV Line	Loss of 765 MW of solar PV resources (27 facilities) Loss of 145 MW of DERs
July 4, 2021 "Tumbleweed"	Phase-to-Phase Fault on 500 kV Line	Loss of 605 MW of solar PV resources (33 facilities) Loss of 125 MW at natural gas facility Loss of 46 MW of DERs
July 28, 2021 "Windhub"	Single-Line-to-Ground Fault on 500 kV Circuit Breaker	Loss of 511 MW of solar PV resources (27 facilities) Loss of 46 MW of DERs
August 25, 2021 "Lytle Creek Fire"	Phase-to-Phase Fault on 500 kV Line	Loss of 583 MW of solar PV resources (30 facilities) Loss of 212 MW at natural gas facility Loss of 91 MW at a different natural gas facility

* 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

Casio Solar Loss Event Report



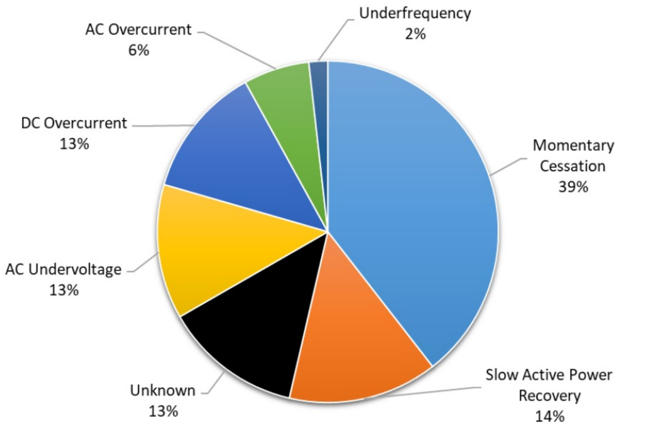


Figure 2.1: June 24 Disturbance Causes of Solar PV Reduction

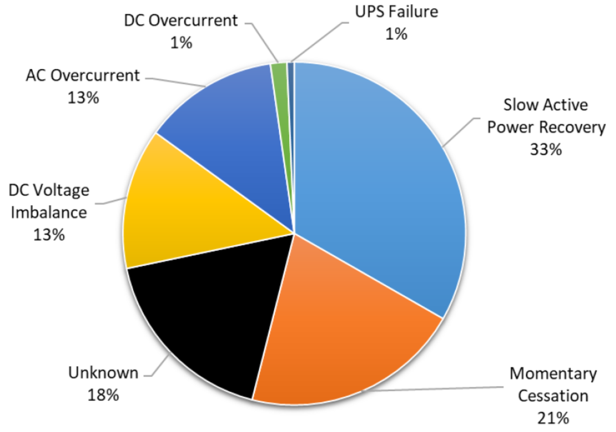


Figure 2.2: July 4 Disturbance Causes of Solar PV Reduction

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Causes of Solar PV Reduction

Table 2.1: Causes of Reduction				
Cause of Reduction	**June 24 [MW]**	**July 4 [MW]**	**July 28 [MW]**	**August 25 [MW]**
Slow Active Power Recovery	111	193	184	91
Momentary Cessation	310	120	192	447
Cause Unknown	103	103	112	24
Inverter DC Voltage Unbalance	-	77	15	4
Inverter AC Overcurrent	49	74	17	13
Inverter DC Overcurrent	98	9	47	3
Inverter UPS Failure	-	4	-	-
Inverter Overfrequency	-	-	43	18
Inverter Underfrequency	14	-	-	-
Inverter AC Undervoltage	100	-	16	-
Total	**785**	**566**	**626**	**600**

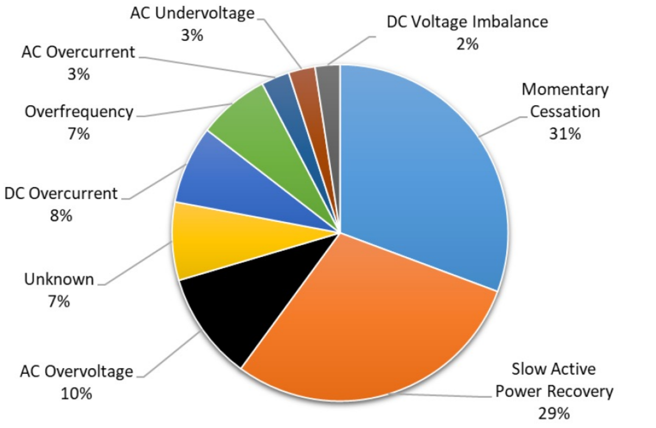


Figure 2.3: July 28 Disturbance Causes of Solar PV Reduction

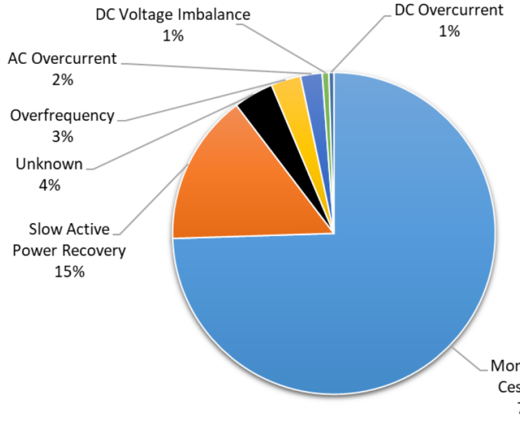


Figure 2.4: August 25 Disturbance Causes of Solar PV Reductions

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

Odessa Report

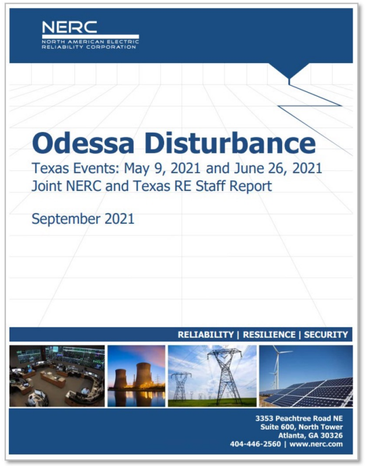
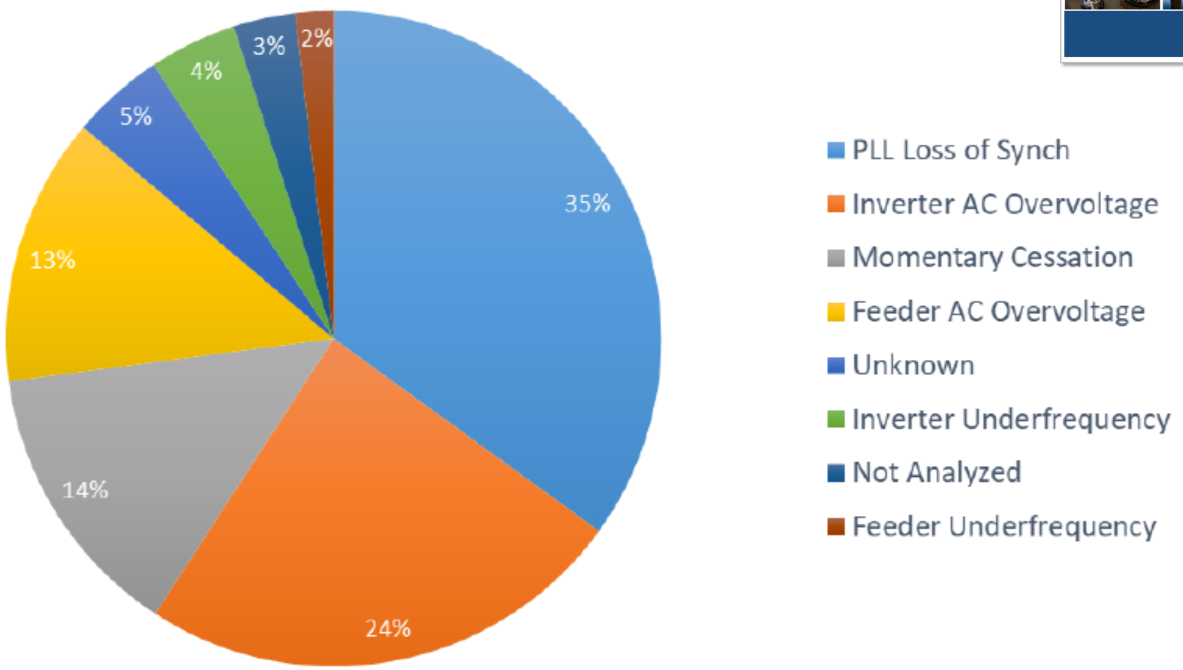
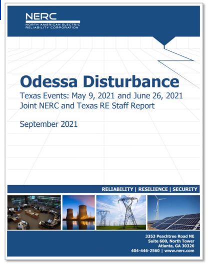


Table 1.1: Causes of Reduction	
Cause of Reduction	**Reduction [MW]**
PLL Loss of Synchronism	389
Inverter AC Overvoltage	269
Momentary Cessation	153
Feeder AC Overvoltage	147
Unknown	51
Inverter Underfrequency	48
Not Analyzed	34
Feeder Underfrequency	21



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

Odessa Report Findings: Performance Assessment and Mitigation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Odessa Disturbance

Texas Events: May 9, 2021 and June 26, 2021

Joint NERC and Texas RE Staff Report

September 2021

RELIABILITY | RESILIENCE | SECURITY

- 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).

Requirement	Compliance at PCC achieved by:	Type tests	DER evaluation	Commissioning tests
6.4 Voltage				
6.4.1 Mandatory voltage tripping requirements	DER System	R	Design: R[a] Installation: R[b]	D
	Composite	L	Design: R[a] Installation: R[b]	D
6.4.2.1 General requirements and exceptions	DER System	R	R	D
	Composite	L	R	D[a]
6.4.2.2 Voltage disturbances within continuous operation region	DER System	R	Design: R[a] Installation: R[b]	D
	Composite	L	R	D[a]
6.4.2.3 Low-voltage ride-through (This is a top-level heading and requirements are specified in the subclauses below.)				
6.4.2.3.2 Low-voltage ride-through capability	DER System	R	R	NR
	Composite	L	R	D[a]
6.4.2.3.3 Low-voltage ride-through performance	DER System	R	R	NR
	Composite	L	R	D[a]
6.4.2.4 High-voltage ride-through (This is a top-level heading and requirements are specified in the subclauses below.)				
6.4.2.4.2 High-voltage ride-through capability	DER System	R	NR	NR
	Composite	L	R	D[a]
6.4.2.4.3 High-voltage ride-through performance	DER System	R	NR	NR
	Composite	L	R	D[a]
6.4.2.5 Ride-through of consecutive voltage disturbances	DER System	R	NR	NR
	Composite	L	R	D[a]

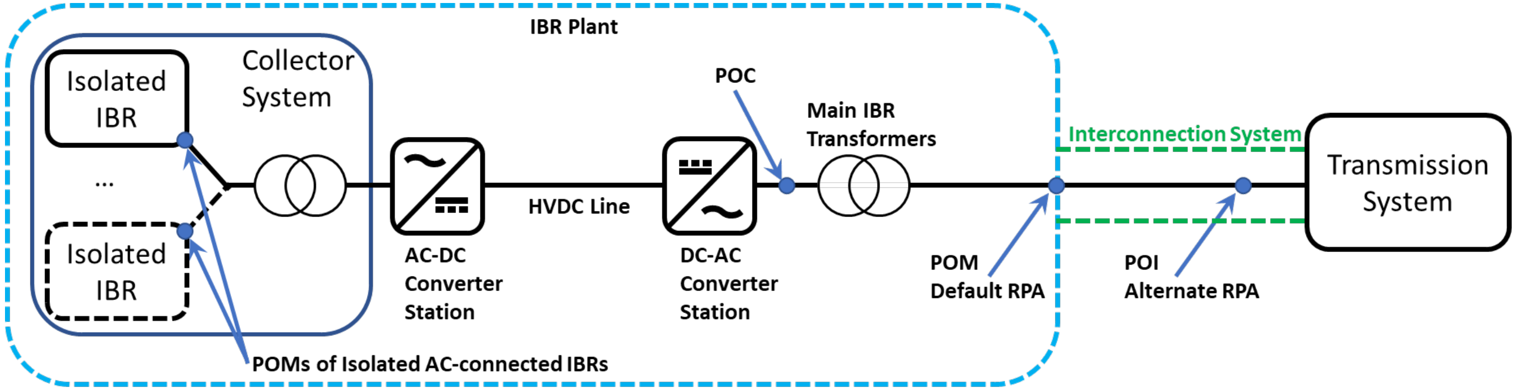
sbunton@epri.com

[a]Align trip settings at DER devices and substation.
[b]Verify correct installation settings.

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

LEGEND	
DER system	DER system is fully compliant at PCC*—no supplemental DER device needed *Individual DER units that are considered fully compliant at the PoC 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.
Composite	Composite of partially compliant DER that is, as a whole, fully compliant at PCC*—may need one or more supplemental DER device(s). *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.
NR	Not Required
R	Required
L	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, leaning on the supplemental equipment to comply.
D	Dependent on DER Design Evaluation
NA	Not Applicable

Relevant Standards: Excerpt from IEEE 2800-2022 Field Test Requirements



IBR – Inverter Based Resources
RPA- Reference Point of Applicability
POC – Point of Connection
POM – Point of Measurement
HVDC – High Voltage Direct Current

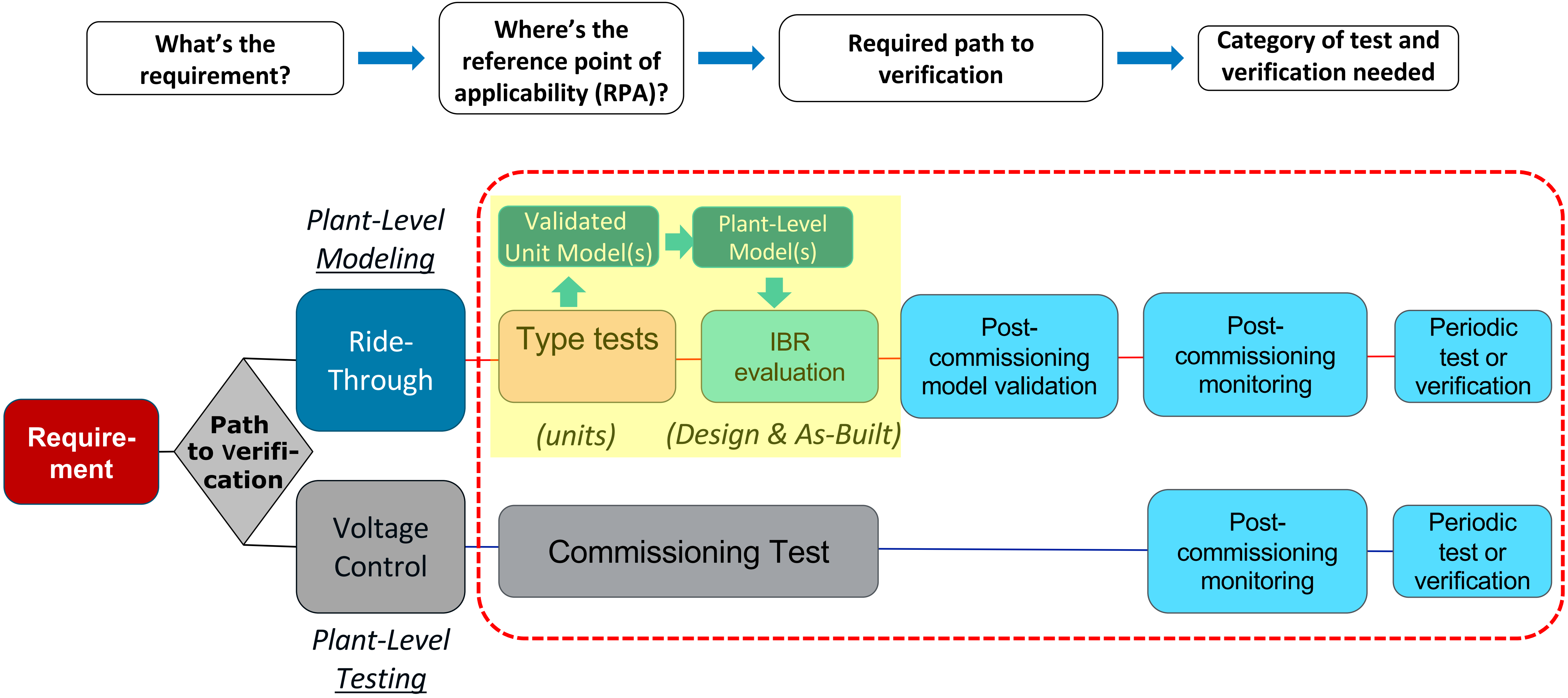
Voltage Disturbance Ride-through Requirements (Clause 7.2.2)

Applicable RPA	IBR Unit-level Tests	IBR Plant-level Verifications at the RPA						
	Test Types	Design Evaluation	Evaluation—As-built Installation	Tests—Commissioning	Validation—Post Commissioning Model	Monitoring—Post-Commissioning	Testing—Periodic	Verification—Periodic
	Entity Responsible							
	Device Manufacturer / IBR Unit / Supplemental IBR	TS Operator/TS Owner / IBR Developer	TS Operator/TS Owner / IBR Developer	TS Operator/TS Owner / IBR Developer	TS Operator/TS Owner / IBR Developer / IBR Operator	TS Operator/TS Owner / IBR Developer	TS Operator/TS Owner / IBR Developer	TS Operator/TS Owner / IBR Developer
	Clause 7 Response to TS Abnormal Conditions							
POC* & POM **	R	R	R	***NR***	***R***	***R***	D	D

*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



How Could Testing be Done?

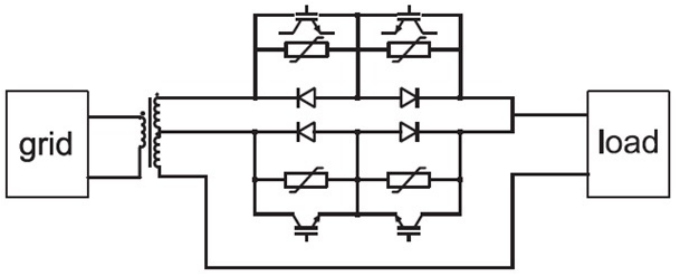
Test Equipment ? Common Sag Generator Types

- 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.

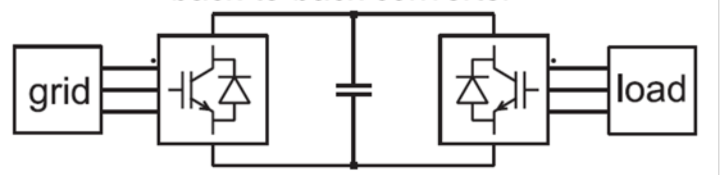
- A third form of sag generator is commonly referred to as the ***impedance divider*** type, which uses a thyristor-controlled reactor to switch impedances for creating voltage sags.
  - Generally, the impedance-divider sag generator weighs less than the other types of sag generators and provides maximum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

Transformer-Switch



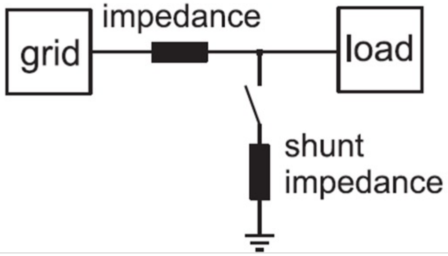
Generalized Form

Amplifier



Generalized Form

Impedance-Divider

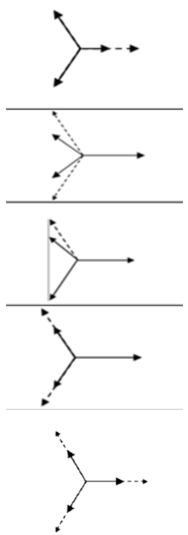


Generalized Form

EPRI: Pioneered Transformer-Switch Type

200A EPRI Tri-Mode Porto-Sag

<u>*Sag Types Per IEEE 1668*</u>



Type I

Type II

Type IIA.1

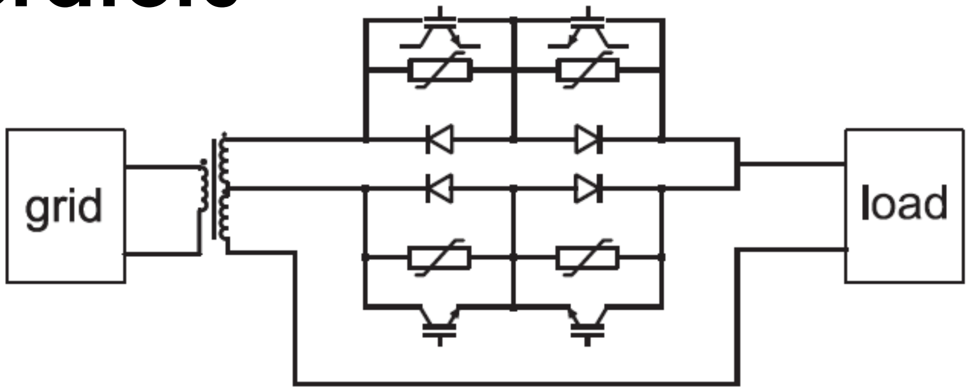
Type IIA.2

Type III

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***

Generalized Form



200A EPRI Tri-Mode Porto-Sag

200A VSG

20A VSG

Sag Corrupter (Powerside) (200A)

Voltage Sag Generator (VSG) (Omniverter)

Approaches

Large Transformer-Switch Type Voltage Sag Generator

Voltage Manipulation Only

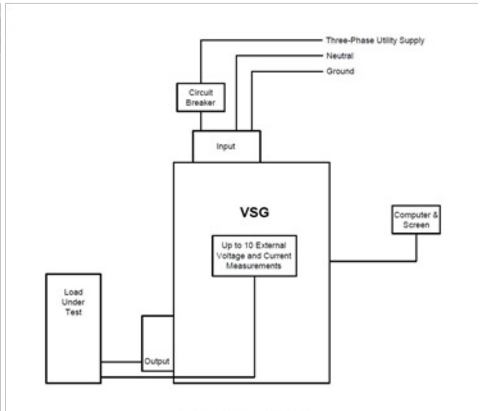
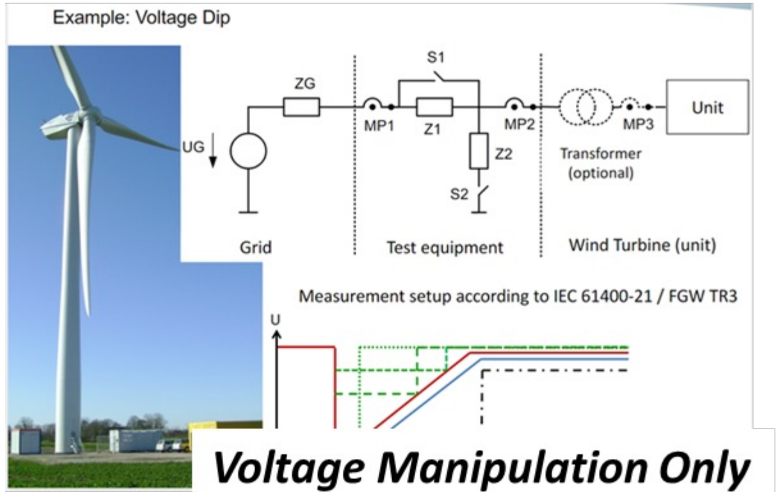


FIGURE 1: VSG TEST SETUP

Impedance Divider



Voltage Manipulation Only

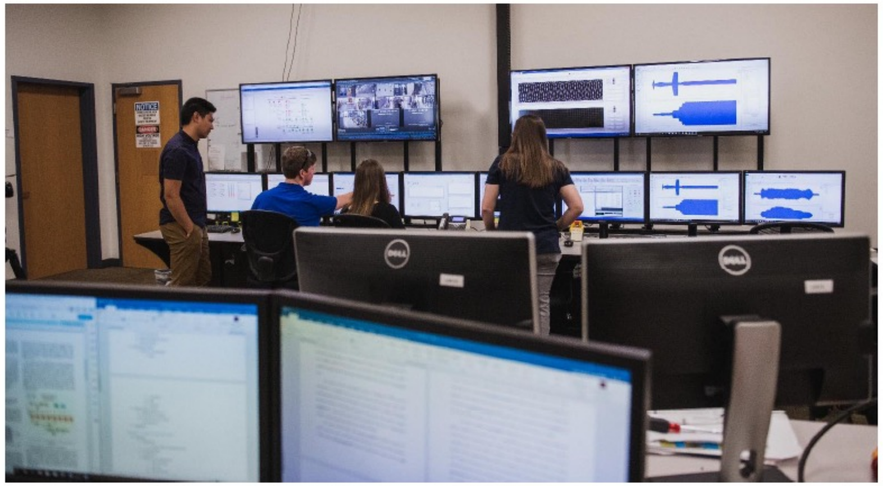
Amplifier/Grid Simulator Based Systems

Voltage & Frequency Manipulation

Would need to be Mobile

DOMINION ENERGY INNOVATION eGrid

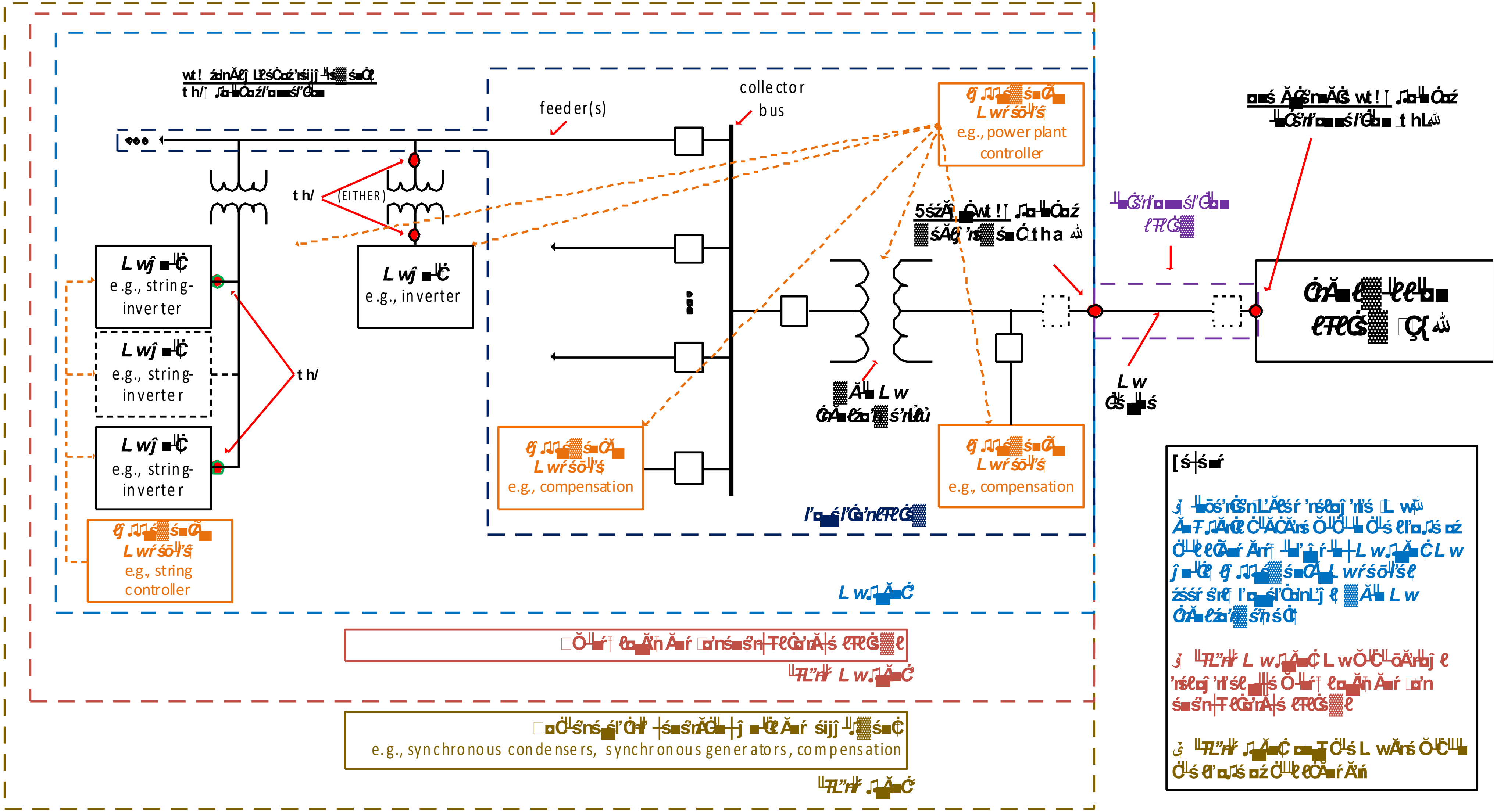
Harmonic Filter



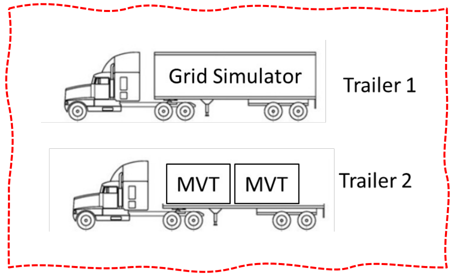
15 MW HIL Grid Simulator Performance Specifications	
Test Power	15000 kVA
Frequency range	45…65 Hz
Sequence capability	3 and 4 wire
High Voltage Ride Through HVRT	100…145%
Low Voltage Ride Through LVRT	100…0%
Unsymmetrical LVRT	yes
Power quality PQ evaluation	yes

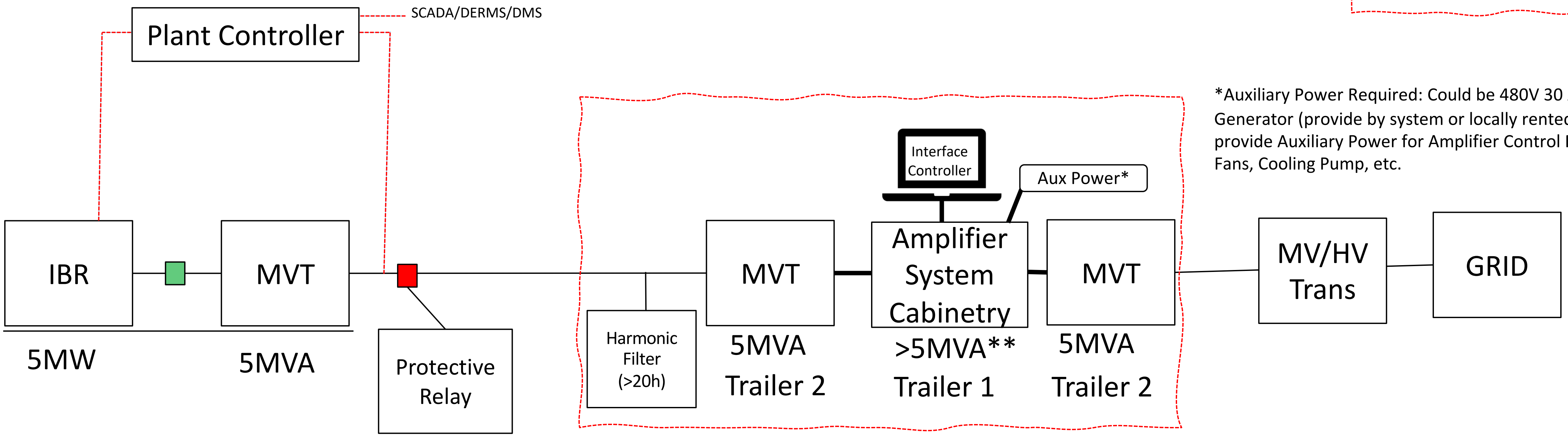
Imagining The Mobile Test System

IEEE 2800 Transmission Connected IBR Options



Brainstorming Mobile Test System Components





*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.

Standardized Connectors and Cabling

Point-of-measurement (POM)

Point-of-connection (PoC)

Test Setup Medium Voltage Transformers (MVTs):

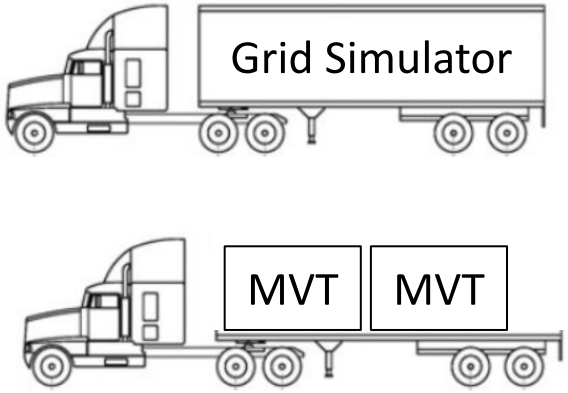
- May not need to be continuous power rated.
- Must have multiple Taps to Interface with different System Voltages

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

**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.

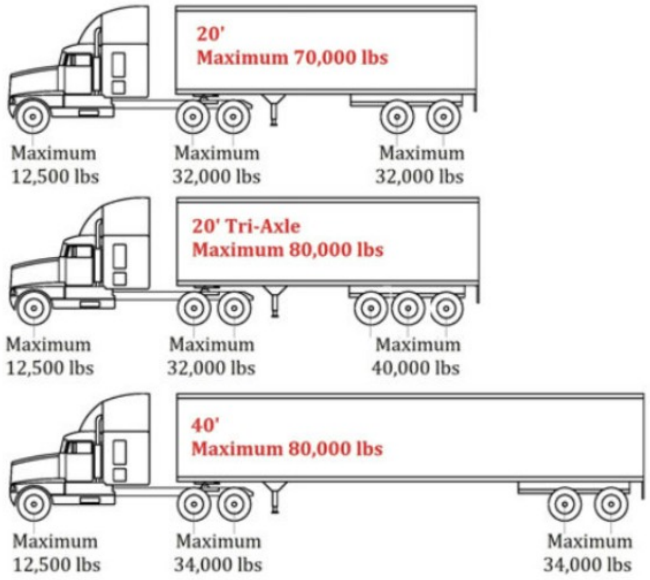
Should Fit within Standard Trailer Dimensions Weight Capacities.

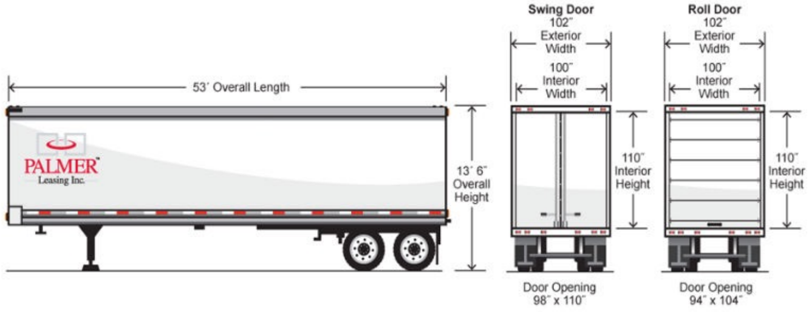


Trailer 1

Trailer 2

Standard Sizes and Weights





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!