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POWER CONSULTING LLC



Challenges of Power Electronics for the Future Grid

Reliability Concerns for the Future

Robert W. Cummings 23 August 2022

Disclaimer and Credits

- All graphics and information used in this presentation are from various reports and presentations given by NERC – all are in the public domain.
- The opinions expressed in this presentation are those of Robert W. Cummings from 45 years of experience in the electric power industry:
 - 6 years – Central Vermont Public Service (System Planning – Gen. and Transmission)
 - 8 years – Public Service Company of New Mexico (Operations Engineering and Wide Area Planning)
 - 8 years – East Central Area Reliability Coordination Agreement (ECAR – Manager of Transmission Services)
 - 23 years – North American Electric Reliability Corp. (NERC – retired in 2020 as Senior Director of Engineering and Reliability Initiatives)

Student of the System

- I am a Student of the System
 - 45 years of observing how the system behaves, especially during abnormal conditions
 - Constantly observing how the system reacts
 - Everything happens for a specific reason – there is no such thing as a “sympathy trip”
 - Think Interconnection-wide – that is the way the system reacts
 - Don’t try to bend the physics – Kirchoff’s Law is immutable
- Principal Investigator in over 15 major system disturbances (and many near-misses)
 - First forensic analysis – Western Interconnection disturbance 29 February 1984
 - 2003 Northeast Blackout through 2015 Washington, DC Area Low Voltage Disturbance
 - Contributor on Inverter-Based Resource disturbances 2016 through Present

The Changing Grid

Where we ~~are~~ were

- The electric grid of North America is a system of central generating stations with large rotating machines – we've had over 100 years to learn how the physics works
- Load consisting of synchronous motors, resistive loads, and incandescent lights

Where we are going

- A system of smaller distributed resources, **largely connected through inverters (IBRs)**
- A large portion of resources are variable (wind and solar) with much lower capacity factors
- Energy storage systems will be essential to continuous power availability
- **Variable speed drive motors** connected by power electronics
- Lighting rapidly moving to LEDs – far less incandescent, CFL, or mercury vapor lights
- Chargers for everything from phones to electric vehicles
- Quantum leaps in power requirements for electrifying transportation

So...how do we get from here to there without adversely effecting reliability?

Reliability Begins at Device Design – What we have seen

- Desired characteristics and *capabilities* must be designed into the devices
- Reliability Starts during the Interconnection Process
 - User-defined models reflective of actual installed (planned) equipment, controls, settings, modes, and protection is critical
 - Models must match actual equipment behavior; otherwise, reliability studies are useless
 - Suite of accurate models is critical to conducting adequate BPS reliability studies
 - Each model type plays a unique role in different types of reliability studies
- Observed threats to reliability – What we have seen
 - Inexperience of the Industry with IBRs and their control systems
 - Behavior of Inverters on Utility Scale – momentary cessation faster than system protection for faults
 - Lack of accurate models for IBRs – Models do NOT reflect reality
 - Shades of BAD MODELING of synchronous machines before the 1996 Western Blackout (9 States)
 - IBR reactions to common switching surges

Threats to Reliability from Inverter-Based Resources

- **What don't we know yet**
 - **Inexperience** of the Industry with IBRs and their control systems
 - **Inter-area oscillations** modes and mode shapes changing by IBRs supplanting synchronous generation
 - **IBR controls interaction**
 - **Common mode failures** for IBRs over large areas
 - **Behavior of IBRs during protracted faults** (remote breaker failure protection clearing in around 20 cycles)
 - **Locating source(s) of Forced oscillations** caused by digital control system and their INTERACTIONS
 - **Relay loadability** – possible on HV and LV transmission (solved on EHV systems)
 - **IBR behavior during FIDVR** (Fault-Induced Delayed Voltage Recovery) events

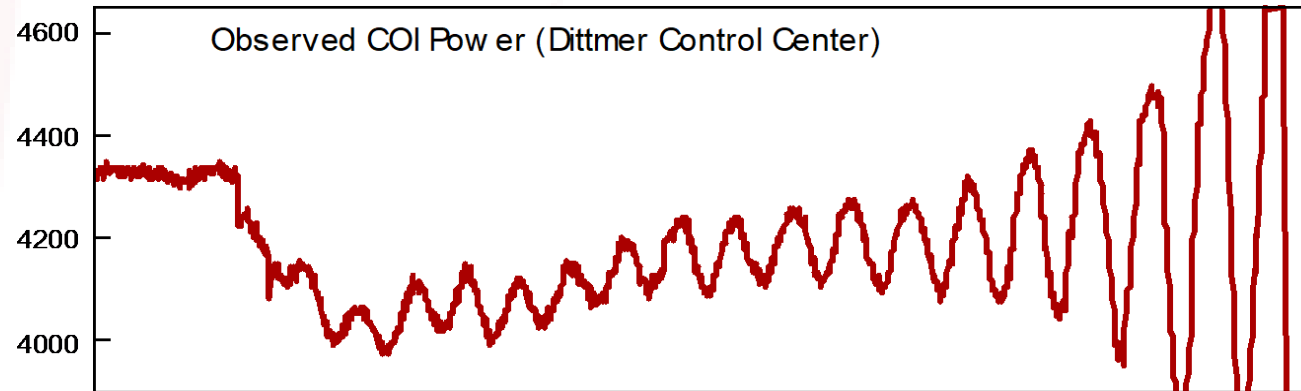
Modeling Issues

You can't always believe models

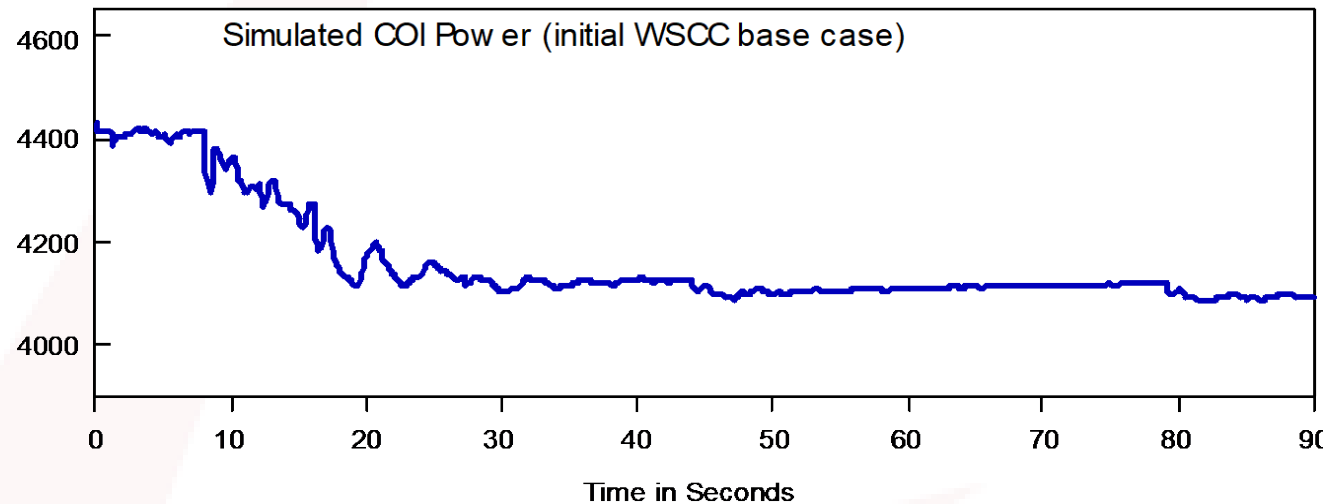
10 August 1999 WSCC Blackout – Models vs Reality

- Don't be overly dependent on models!

Real event



Dynamic simulations



No confidence in dynamics database

Major Recommendation and Modeling Issues – 1996 WSCC Blackout

- **DO NOT** operated the system in unstudied configurations and loading levels!
- Dynamic models are terrible...called for establishment of generator testing to obtain as-built physical characteristics and control parameters.
- If something is not modeled, how can you predict system behavior or interaction????

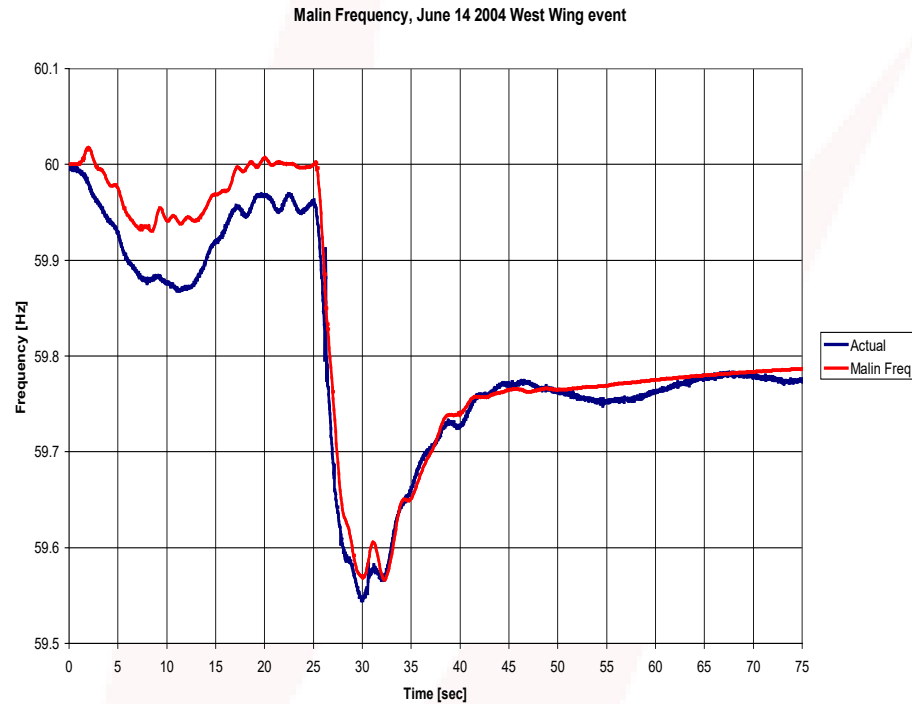
1996 Dynamics Modeling Issues

- Missing models
- Data errors
- Models may not match field equipment and settings
- Issue of “proprietary models”
- No models for many wind farms (PV was not prevalent yet)
 - No good indication of where wind farms are connected

Improved Confidence after Machine Testing – Simulations – of 14 June 2004 Event

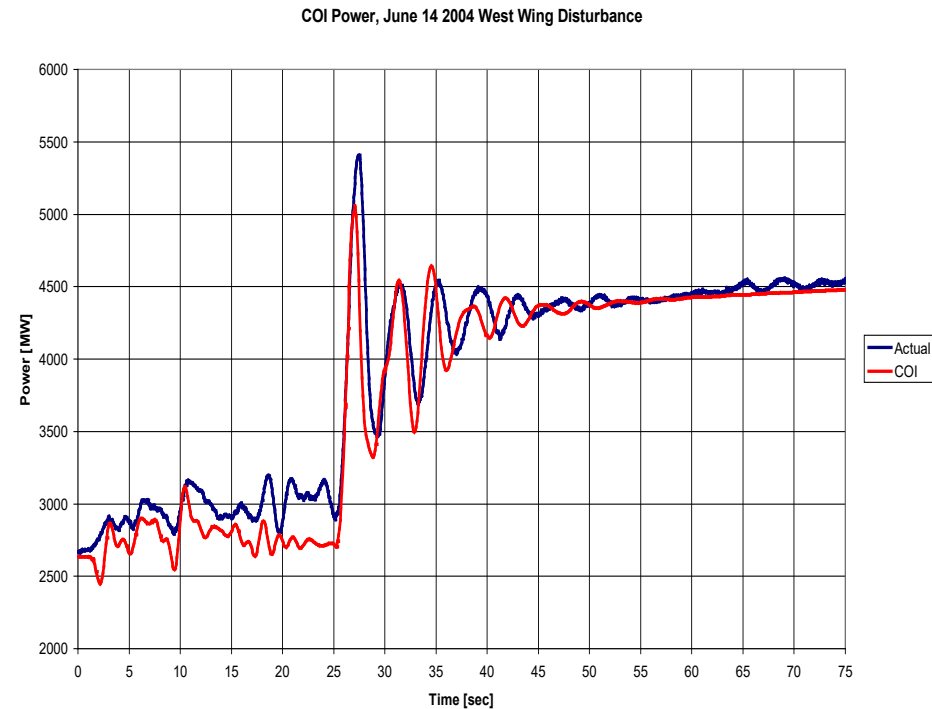
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Frequency Response



— Real event
— Simulations

COI Power Flows



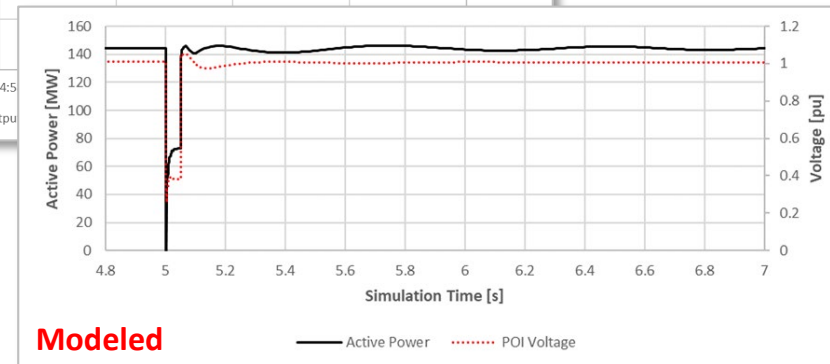
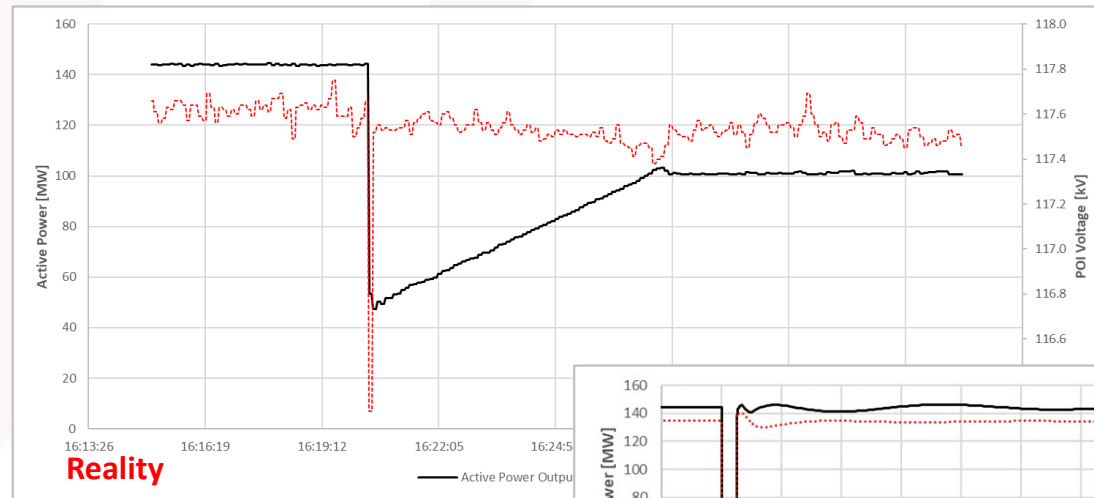
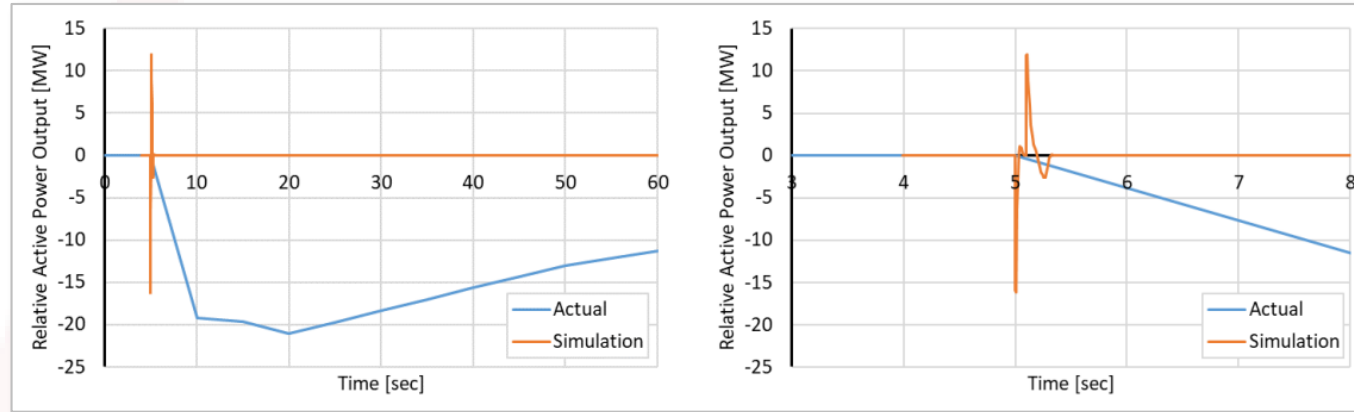
Basic Tenets of Modeling and Predictive Studies

- To predict performance, you MUST be able to understand the system's behavior.
- To understand the system's behavior, you MUST observe and measure its actual behavior.
- Once you understand the system's behavior, you MUST be able to model it, both as individual models and as a full Interconnection
- Once you are able to model the system's behavior, you can predict its performance. If you can't model it, you cannot predict system behavior

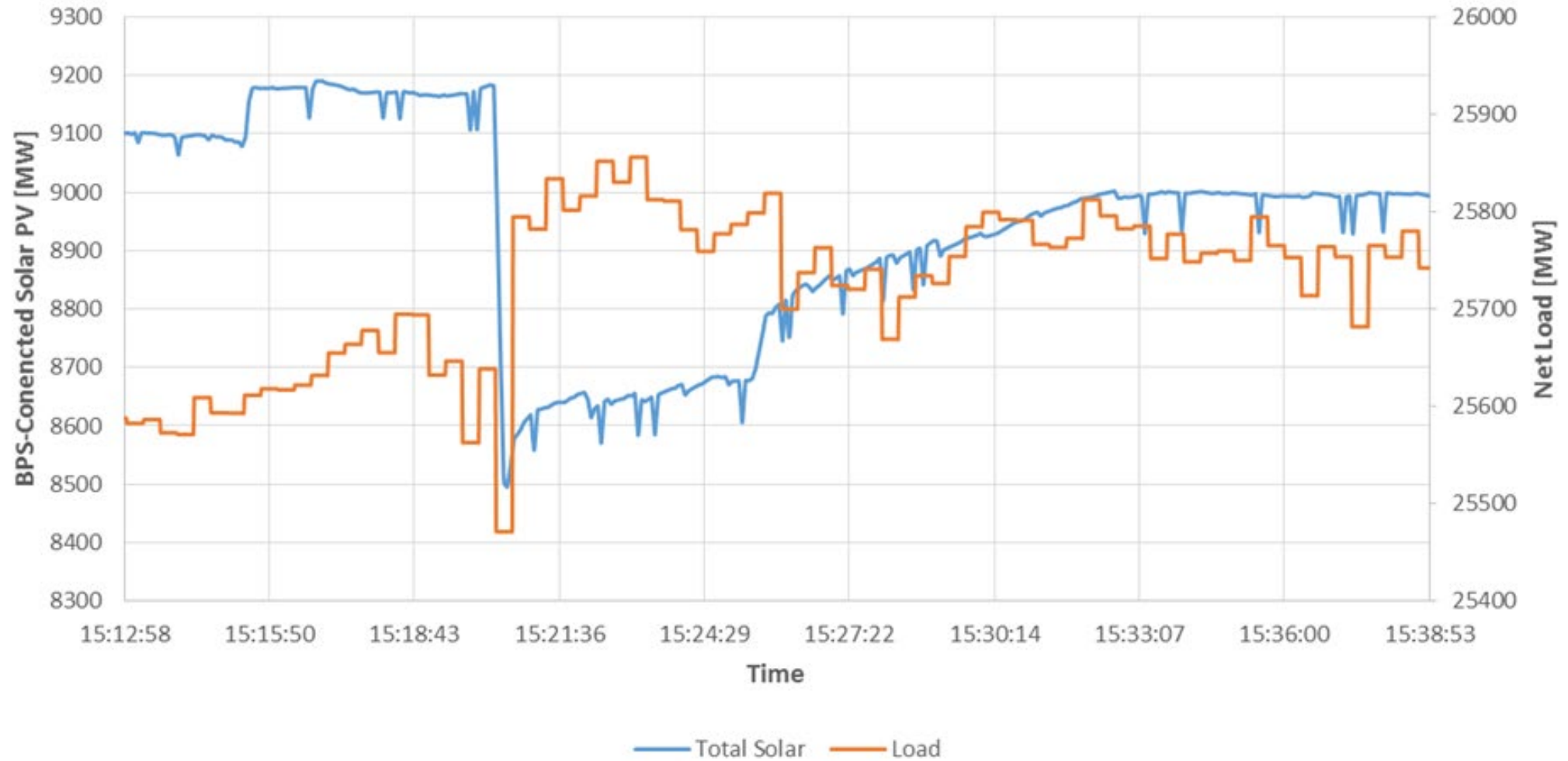
Model Validation for Recent WECC IBR Disturbances

Accurate modeling is critical to BPS reliability

Inaccurate Models = Inaccurate Studies = Inaccurate Reliability Decisions



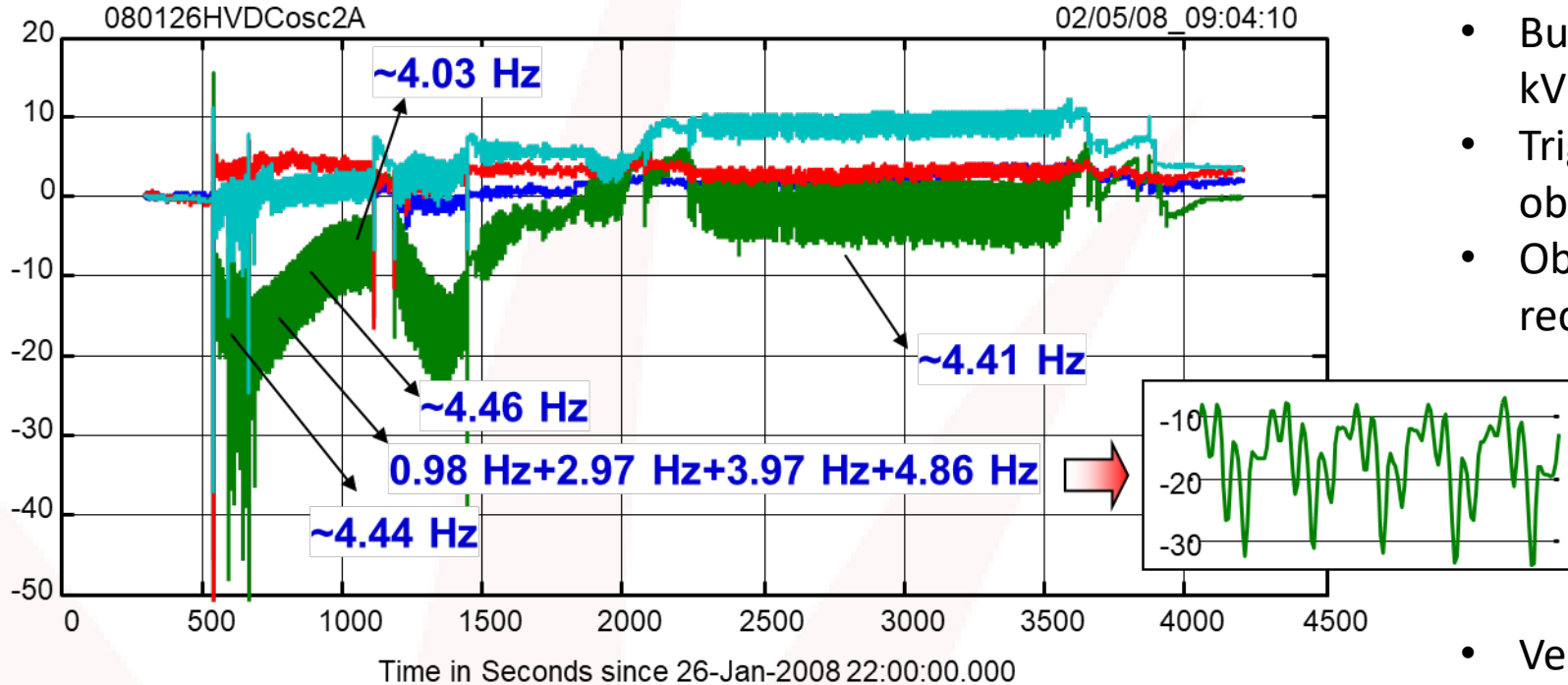
Palmdale Roost Disturbance – CAISO BPS-Connected Solar and Net Load



WECC Pacific DC Intertie Forced Oscillations

26 January 2008

080126HVDCosc2A Swings



—	MALN Malin N.Bus Voltage	VMag
—	BE23 Big Eddy 230 Bus3 Voltage	VMag
—	BE50 Big Eddy 500 Bus Voltage	VMag
—	SYLM Sylmar Bus Voltage	VMag

- Bushing failure on Big Eddy 500/230 kV Transformer
- Triggered oscillations – not observable on SCADA
- Observed on venerable strip recorder at SCE

- Verified by phasors – PDCI controls determined to be responsible – 500 kV and 230 kV sources separated at northern end

Recommendations on Power Electronic Development

- IEEE Standard 1547 should NOT be used or applied to BPS-connected resources
- Sometimes, fast is too fast! The grid cannot tolerate most things acting in 10 mS or faster!
- There is no such thing as an infinite bus! All devices connected to the grid may interact with the grid and with each other, often across great distances (1,000+ miles). Avoid the use of the term “neighboring system.”
- Myopic analysis of a company or RTO system is inadequate...analysis MUST be done on and Interconnection scale!
- We have the computing power to analyze several protection/control schemes (including RAS) together – LET’S USE IT!
- Always think about what the new PE device might be faced with – what will the system throw at the device?

NERC Inverter-Based Resource Analyses and Guidelines

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Technical Report

BPS-Connected Inverter-Based Resource Modeling and Studies

May 2020

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Reliability Guideline

BPS-Connected Inverter-Based Resource Performance

September 2018

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Utilizing the Excess Capability of BPS-Connected Inverter-Based Resources for Frequency Support

NERC Inverter-Based Resource Performance Working Group (IRPWG)
White Paper
September 2021

The Federal Energy Regulatory Commission (FERC) issued Order No. 842 in 2018, amending the pro forma Large Generator Interconnection Agreement (LGA) and Small Generator Interconnection Agreement (SGA) to require all "newly interconnecting large and small generating facilities, both synchronous and non-synchronous, to install, maintain, and operate equipment capable of providing primary frequency response (PFR) as a condition of interconnection." On the same subject, NERC recently published a white paper, *Fast Frequency Response Concepts and Bulk Power System Reliability Needs*. In March 2020 describing the interrelationships between primary frequency response (PFR) and fast frequency response (FFR), this work extends on the FERC Order No. 842 and the NERC white paper and recommends leveraging PFR and FFR capabilities from inverter-based resources to the extent possible to support BPS frequency as an essential reliability service.

Specifically, inverter-based resources operating at their maximum contractual agreement, also referred to as the steady-state interconnection limit (SSL), may be able to support the grid during underfrequency events beyond their SSL. This situation is most likely to occur in "accoupled" hybrid plants (i.e. the combination of battery energy storage and wind or solar PV) or in standalone wind, solar PV, and battery energy storage plants where additional capacity is available but not presently utilized due to the SSL constraints imposed by interconnection agreements. It should be noted that this paper only focuses on the excess capability of inverter-based resources that is limited by the SSL; it does not consider the short-term overload capability of individual inverters.

By establishing a short-term interconnection limit (STIL) in interconnection agreements, inverter-based resources with excess active power capability beyond SSL can use this capability to better support the grid frequency. However, once the system frequency recovers to nominal, the MW output of the plant should

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Reliability Guideline

Improvements to Interconnection for BPS-Connected Inverter-Based Resources

September 2019

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Reliability Guideline

Performance, Modeling, and Simulations of BPS-Connected Battery Energy Storage Systems and Hybrid Power Plants

March 2021

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Key Takeaways

Inverter Manufacturer and Relay Manufacturer

April 2019

NERC facilitated an in-depth technical discussion between inverter manufacturers and relay manufacturers, and industry experts related to current inverter designs, fault conditions and potential impacts on protection systems (relays, protection schemes). The following key takeaways, recommendations, and next steps were an outcome of this discussion.

General Takeaways

- Industry needs to collectively speak in terms of phase imbalance rather than sequence components, to better understand the underlying cause regarding current injection during faults. Sequence components are a tool for analyzing unbalanced three-phase power systems, and are derived from phase quantities.
- Protection engineers setting protective relay settings do not generally use electromagnetic transient (EMT) simulation programs. Short-circuit programs typically used by protection engineers do not accurately represent the dynamic response of inverter-based resources during the first few cycles after fault inception as the phase and sequence components may not stabilize.
- The injection of negative sequence current (I2) from generating resources during unbalanced fault events is beneficial for existing protection schemes and SPS stability. All resources, where possible, and in the future, should maintain the correct phase relationship between the unfaulted phases and faulted phases both in voltage and current. This ensures predictable phase relationship between sequence voltages and currents, and consequently operation and protection behavior that is consistent with conventional power system operation.
- Inverter-based resources respond to faults based on the controls programmed into the inverter. Controlled inverter response generally does not start to occur until one electrical cycle (measurement and processing time delay) from fault inception. During the first couple of electrical cycles of a severe fault, the assistance from inverter-based resources may be distributed to a less than optimal level.
- The concept of critical inverter-based response setting primary protection.

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Reliability Guideline

BPS-Connected Inverter-Based Resource Performance

September 2018

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Grid Forming Technology

Bulk Power System Reliability Considerations

December 2021

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Fast Frequency Response Concepts and Bulk Power System Reliability Needs

NERC Inverter-Based Resource Performance Task Force (IRPTF)
White Paper

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San Fernando Disturbance Follow-Up

NERC Inverter-Based Resource Performance Working Group (IRPWG)
White Paper – June 2021

This brief white paper was developed by the NERC Inverter-Based Resource Performance Working Group (IRPWG) as a follow-up to the July 2020 San Fernando Disturbance Report published by NERC. That report contained a set of key findings and recommendations. The IRPWG developed each of the key findings and recommendations in detail, provides a brief technical discussion and basis for each item, and where appropriate, recommends follow-up action items. Table 1 shows the key findings and recommendations from the NERC disturbance report on the left-hand column and the IRPWG follow-up and recommendations for each item in the right-hand column.

The following are the recommended actions from the IRPWG report:

- FERC should integrate the recommendations from the San Fernando report and the IRPWG guidelines into the pro forma LGA for all newly interconnecting inverter-based resources. The future FERC 842 Standard Drafting team should consider P2000 Clause 11 efforts, and ensure that the modifications require disturbance monitoring equipment of inverter-based resource facilities.
- IRPWG will continue summarizing lessons learned from the events with systematic causes of inverter tripping. IRPWG in future publications better gaps, guidelines, SARs and IECs and NERC, in coordination with industry, should develop a coordinated strategy to ensure the effective and widespread adoption of IEEE P2000 once it is approved.
- IRPWG should continue to address the outstanding recommendations by NERC to address the issue identified in EOP-024 regarding the generation bus criteria so that it is applicable for inverter-based resources as well synchronous generation.
- Modeling and study standards (e.g., MOC and PFI) should be reviewed by IRPWG to consider the inclusion of EMT models for study purposes by the TP and PC. Currently these studies that would be used to identify possible tripping or abnormal performance from inverter-based resources are not performed only in certain occasions where the TP or PC has identified issues after other modeling tools. However, the issue identified in these disturbances have not been identified or highlighted by the TP or PC in their

IEEE Power & Energy Society

Impact of Inverter Based Generation on Bulk Power System Dynamics and Short-Circuit Performance

July 2018

TECHNICAL REPORT
PES-TR68

PREPARED BY THE
IEEE/NERC Task Force on Short-Circuit and System Performance
Impact of Inverter Based Generation

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Integrating Inverter-Based Resources into Low Short Circuit Strength Systems

Reliability Guideline

December 2017

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Odessa Disturbance Follow-Up

NERC Inverter-Based Resource Performance Working Group (IRPWG)
White Paper – October 2021

This brief white paper was developed by the NERC Inverter-Based Resource Performance Working Group (IRPWG) as a follow-up to the Odessa Disturbance Report published by NERC in October 2021. That report contained a set of key findings and recommendations. The IRPWG developed each of the key findings and recommendations in detail and providing a brief technical discussion and technical basis for each recommendation. Where appropriate, follow-up action items are identified. Table 1 shows the recommendations and actions needed from Chapter 4 of the NERC disturbance report on the left-hand column and the IRPWG follow-up and recommendations for each item in the right-hand column.

The following are the recommended actions from the IRPWG report:

- NERC and NERC should collaboratively modernize the interconnection study process and update NERC Reliability Standards to ensure that LTR recommendations outlined in the reliability guidelines are effectively and consistently connected to performance requirements for inverter-based resources. These requirements should be clearly built into the interconnection, and should be clear, detailed, and enforceable to ensure that developers, equipment manufacturers, and O&M understand the performance requirements needed to ensure reliable operation of the BPS frequency.
- IRPWG will develop standard authorization requests (SARs) related to a number of testing standards and possibly the addition of new standards to address the issue described below.
- IRPWG will conduct a comprehensive assessment, taking into consideration the guidelines and interconnection documents developed by NERC, to determine the performance gaps not addressed by the NERC Reliability Standards and will provide recommendations for additional SARs, where applicable. This assessment will also specifically evaluate the need for any inverter-specific performance requirements language.

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WECC Base Case Review: Inverter-Based Resources

NERC-WECC Joint Report
August 2020

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Questions?