Inverter-Based Resource (IBR) Workshop

April 25, 2019

Agenda

Item	Topic	Presenter
1	Welcome and Introduction	Jeff Billo
2	Review Existing IBR related ERCOT Protocol/Guides	John Bernecker
3	Observations and Potential Proposals	
3.1	Voltage Support and Coordination	John Bernecker
3.2	Momentary Cessation and Voltage Ride Through	Fred Huang
3.3	Voltage Support Capability under Low/Zero Output	Jeff Billo
	Lunch Break	
3.4	Frequency Ride Through and Measurement	Nitika Mago
3.5	Dynamic performance requirement for active power and reactive power	Prabhu Gnanam
3.6	Dynamic Models	Fred Huang
3.7	Measurement and Monitoring	Prabhu Gnanam
3.8	Grid Forming	Julia Matevosjana
4	Summary and Next Steps	

Motivation

- Inverter-based resources (IBR) have moved from niche to mainstream on the ERCOT system
- ERCOT has experienced operational, modeling, and simulation challenges with IBRs
- ERCOT's 2018 Dynamic Stability Assessment High Penetration of Renewable Generation demonstrated potential future challenges with operating and modeling a grid made up mostly of IBRs:
  - http://www.ercot.com/content/wcm/lists/144927/Dynamic_Stability_Assessment_of_High_Penetration_of_Renewable_Generation_in_the_ERCOT_Grid.pdf
- There have been recent reliability events in California
- The NERC Inverter-based Resource Performance Task Force (IRPTF) published a Reliability Guideline in 2018
  - More on this later!

Goals

1

Prevent events that have happened in other regions

2

Address and resolve issues observed in ERCOT Planning and Operations

3

Redirect ERCOT's path before issues are exacerbated with our growing IBR fleet

Logistics

- Workshop focus is on transmission-connected IBRs
- ERCOT Staff will take notes during discussion
  - Notes will be posted after the meeting
- We will maintain a list of issues brought up during the workshop
- At the end of the workshop, we will review the issues and identify next steps

Background: NERC IRPTF

- Inverter-based Resource Performance Task Force
  - 2 Events
    - Blue Cut Fire
    - Canyon 2 Fire
  - And a lot of work!

Background: NERC IRPTF

Disclaimer:

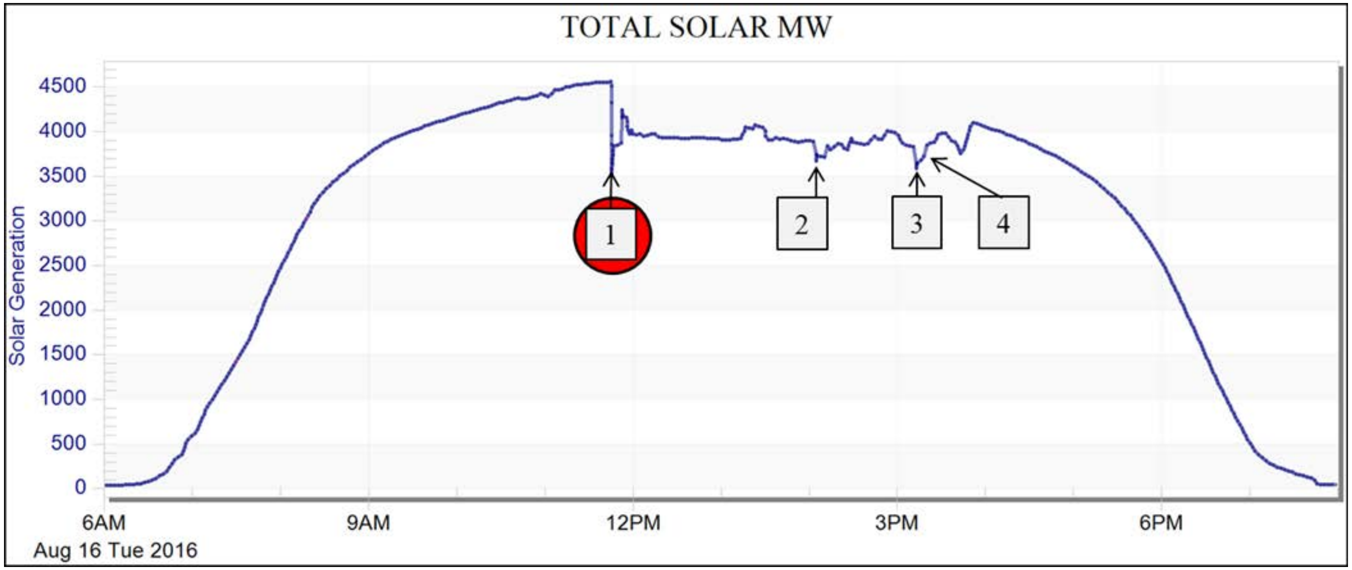
The views and opinions expressed today, though represented by NERC Inverter-based Resource Performance Task Force (IRPTF) members, should not be construed as representing NERC or the IRPTF.

Blue Cut Fire Event Summary

- The Blue Cut Fire began on August 16, 2016
  - Thirteen 500 kV faults
  - Two 287 kV faults
  - Four faults resulted in a loss of solar PV generation
  - Largest event resulted in the loss of ~1,200 MW of solar PV generation

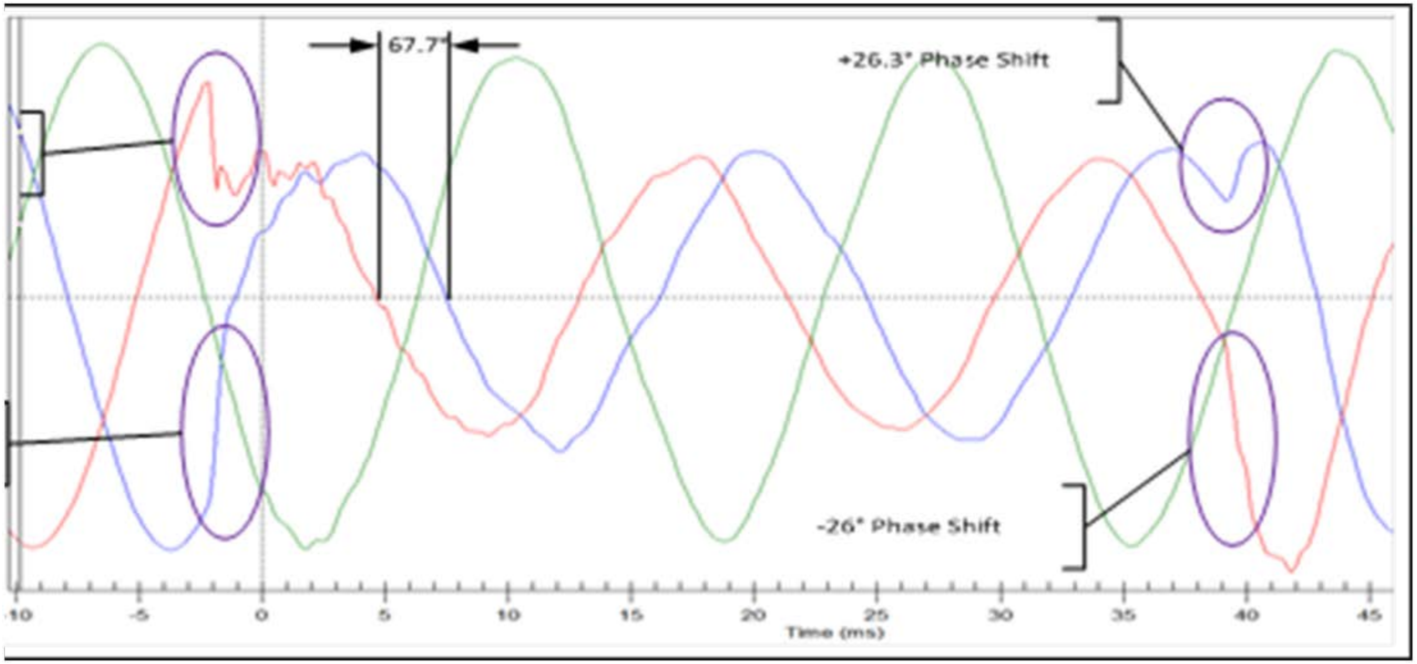
Blue Cut Fire Event

Table 1: Solar Photovoltaic Generation Loss						
#	Date/Time	Fault Location	Fault Type	Clearing Time (cycles)	Lost Generation (MW)	Geographic Impact
1	8/16/2016 11:45	500 kV line	Line to Line (AB)	2.49	1,178	Widespread
2	8/16/2016 14:04	500 kV line	Line to Ground (AG)	2.93	234	Somewhat Localized
3	8/16/2016 15:13	500 kV line	Line to Ground (AG)	3.45	311	Widespread
4	8/16/2016 15:19	500 kV line	Line to Ground (AG)	3.05	30	Localized



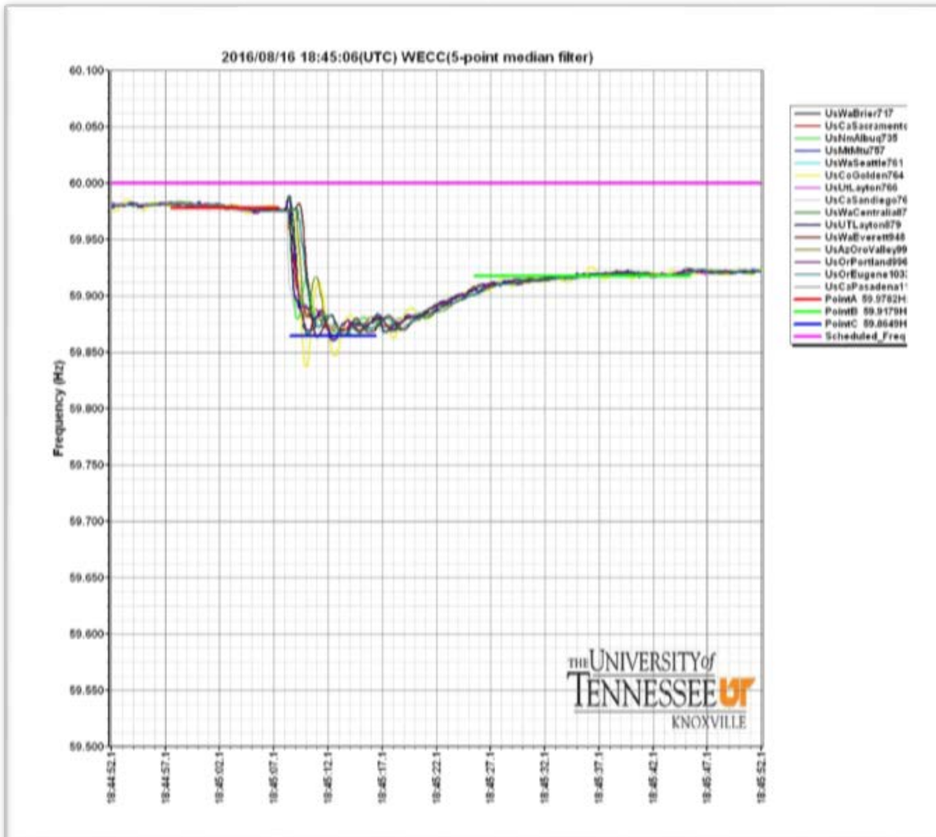
Blue Cut Fire: Initiating Fault

- Faults on the transmission system can cause waveforms to undergo instantaneous phase shifts, voltage sags, and harmonic distortion.
- Phase shifts can be interpreted as frequency deviation
- Line to Line faults cause significantly larger phase shift



Blue Cut Fire: Actual System Frequency

- Frequency Measuring Network data showed that system frequency during the event did not fall below 59.86 Hz.

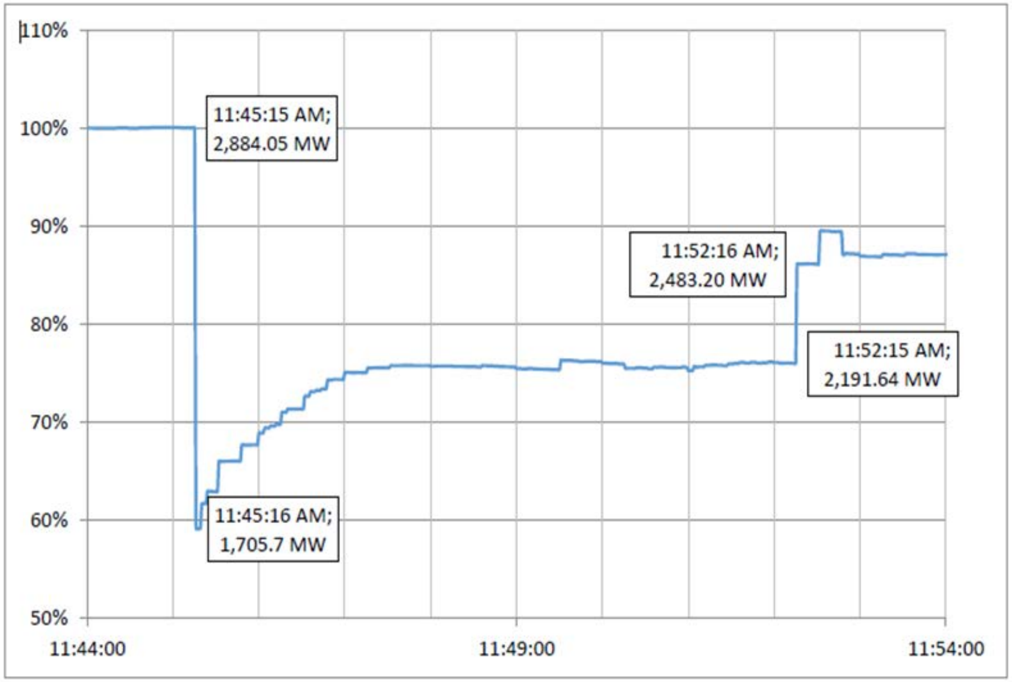


Blue Cut Fire: System Voltage During Event

- The initiating fault was a line-to-line fault, which resulted in a significant and widespread voltage sag below 0.9 pu voltage
  - Fault type (SLG, LL, 3PH) plays a large role in the magnitude
  - Inverters with Momentary Cessation ceased to inject current into the grid while voltage was outside the continuous operating voltage range
    (typically 0.9 pu-1.1 pu) at the time of the event.

Blue Cut Fire 1,200 MW Event Analysis

- ~700 MW of the total resource loss was attributed to a perceived low system frequency.
  - Many inverters were set to instantaneously trip offline if frequency fell below 57 Hz.
- ~450 MW of the total resource loss was attributed to Momentary Cessation.
- ~100 MW attributed to DC overcurrent protection.



Blue Cut Fire: Key Findings

- Instantaneous trip settings combined with near instantaneous frequency measurements can cause inverters to be susceptible to erroneous tripping.
- The majority of inverters were configured to momentarily cease current injection when voltage was outside the range 0.9-1.1 pu.
- The impact of Momentary Cessation needs to be considered in interconnection studies.

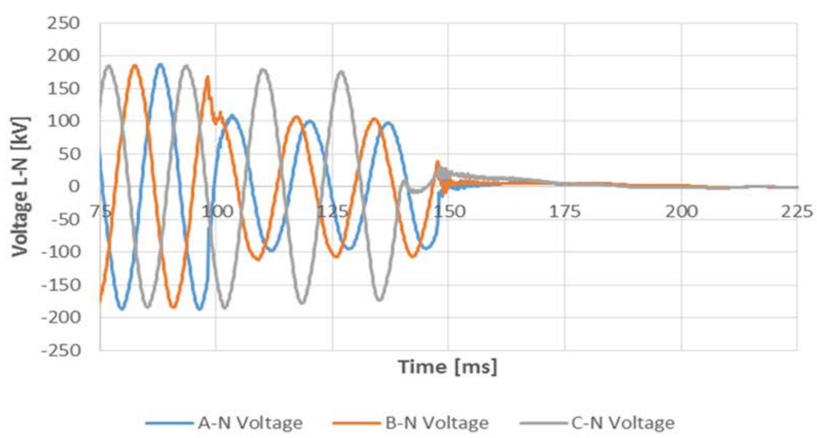
Outcomes

- IRPTF was formed.
- NERC Alert was developed.
- Inverters that were susceptible to erroneous tripping were reprogrammed to prevent them from tripping offline due to miscalculated frequency.
- Event report:

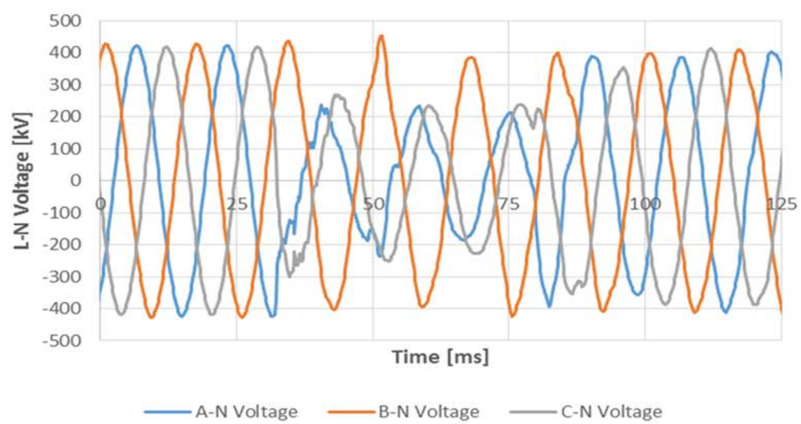
  https://www.nerc.com/pa/rrm/ea/1200_MW_Fault_Induced_Solar_Photovoltaic_Resource_/1200_MW_Fault_Induced_Solar_Photovoltaic_Resource_Interruption_Final.pdf

Canyon 2 Fire Event

- Smoke from nearby fires caused 2 phase-to-phase faults just two minutes apart on October 9, 2017.

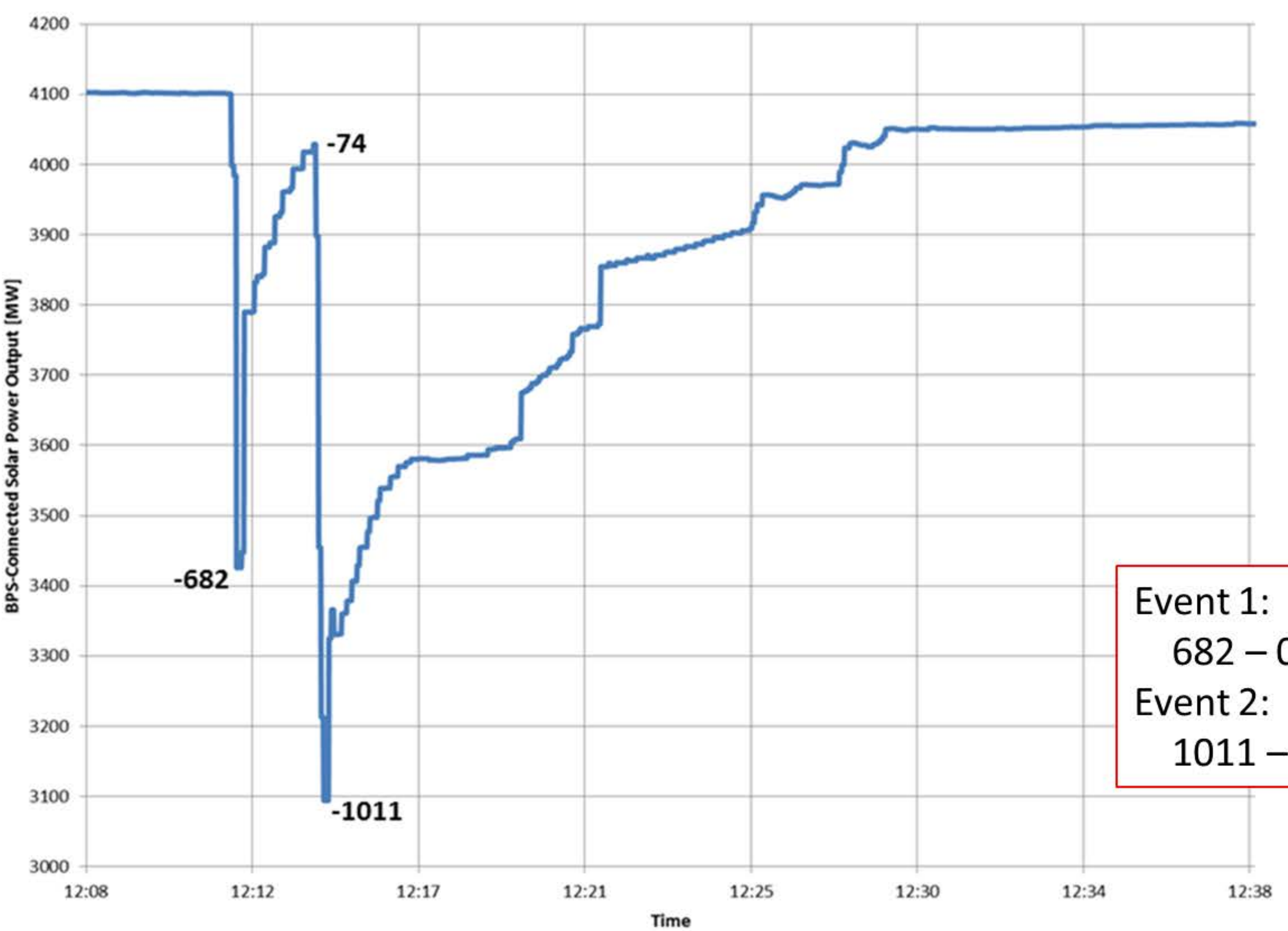


__Fault Event 1 at 12:12:__
220 kV
L-L Fault
< 3 cycle clearing



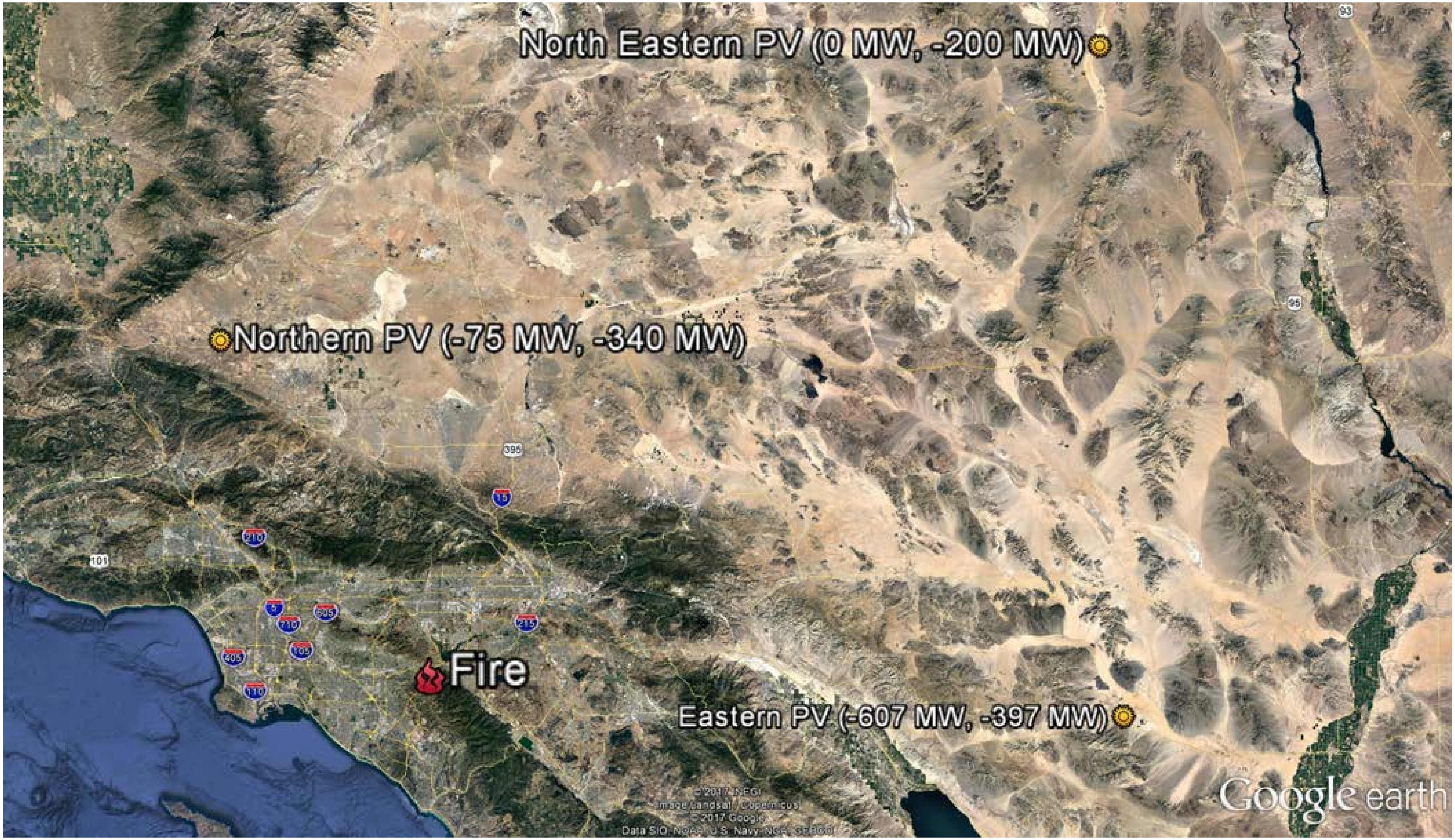
__Fault Event 2 at 12:14:__
500 kV
L-L Fault
< 3 cycle clearing

Canyon 2 Fire Event

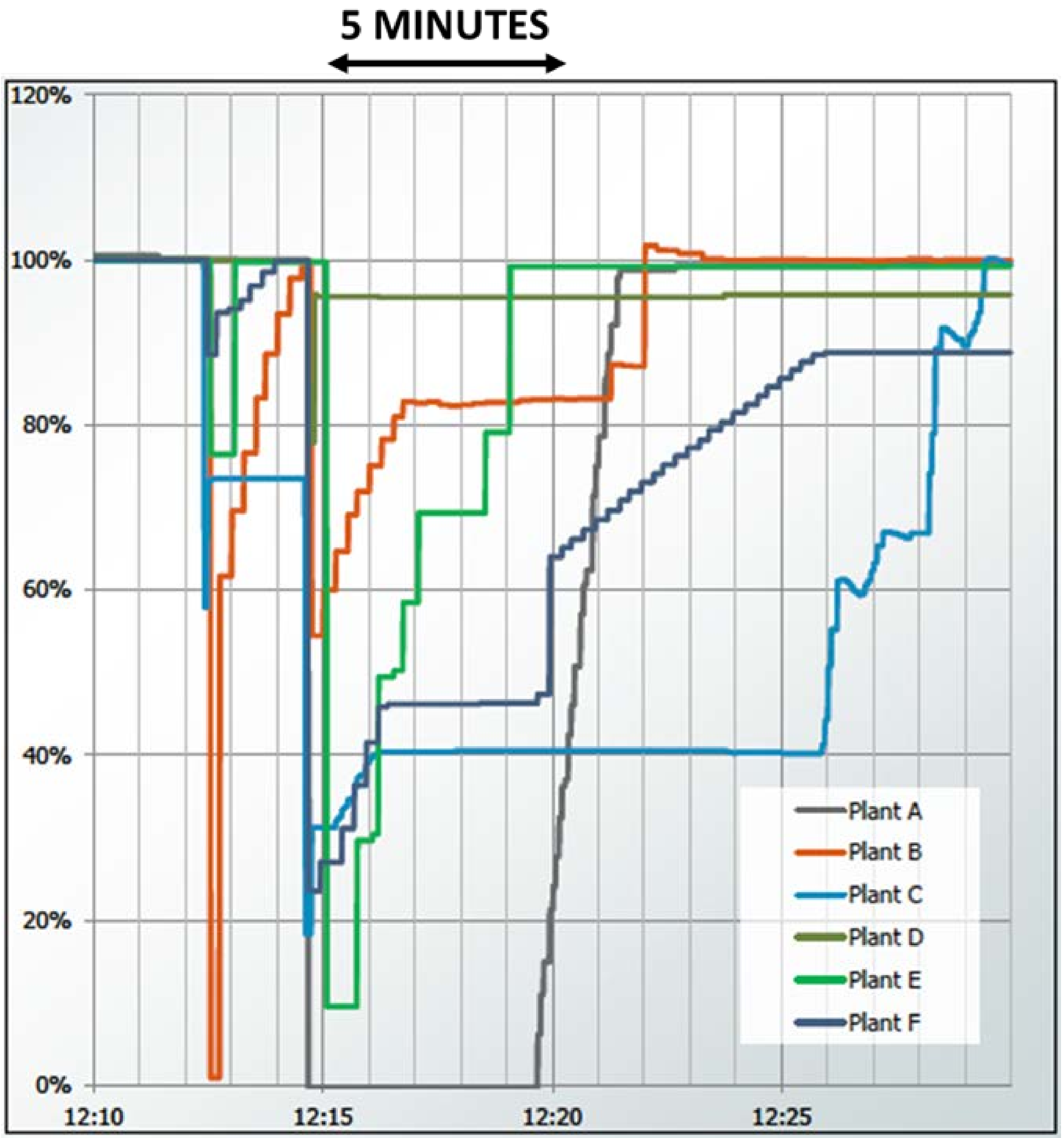


Event 1:
682 – 0 = 682 MW
Event 2:
1011 – 74 = 937 MW

Canyon 2 Fire: Affected Area



Canyon 2 Fire: Individual Solar PV Plant Outputs



Canyon 2 Fire: Key Finding #1

No Erroneous Frequency Tripping

- Erroneous frequency tripping was one of the major issues in the Blue Cut Fire event.
- Alert recommended GOPs and GOs ensure inverter controls do not erroneously trip on instantaneous frequency measurements.
- By October 9, 2017 event, 97% of inverter manufacturer’s BPS-connected fleet had been updated.
- Mitigating actions by inverter manufacturer and GOs appear to have worked.

Canyon 2 Fire: Key Finding #2

Continued Use of Momentary Cessation

- Solar resources continue to use momentary cessation, most commonly for voltage magnitudes outside 0.9–1.1 p.u.
- The use of momentary cessation is not recommended, should not be used for new inverter-based resources, and should be eliminated or mitigated to the greatest extent possible. If it must be used then resources should return active current injection within 0.5 seconds of voltage recovery.

Canyon 2 Fire: Key Finding #3

Ramp Rate Interactions with Momentary Cessation

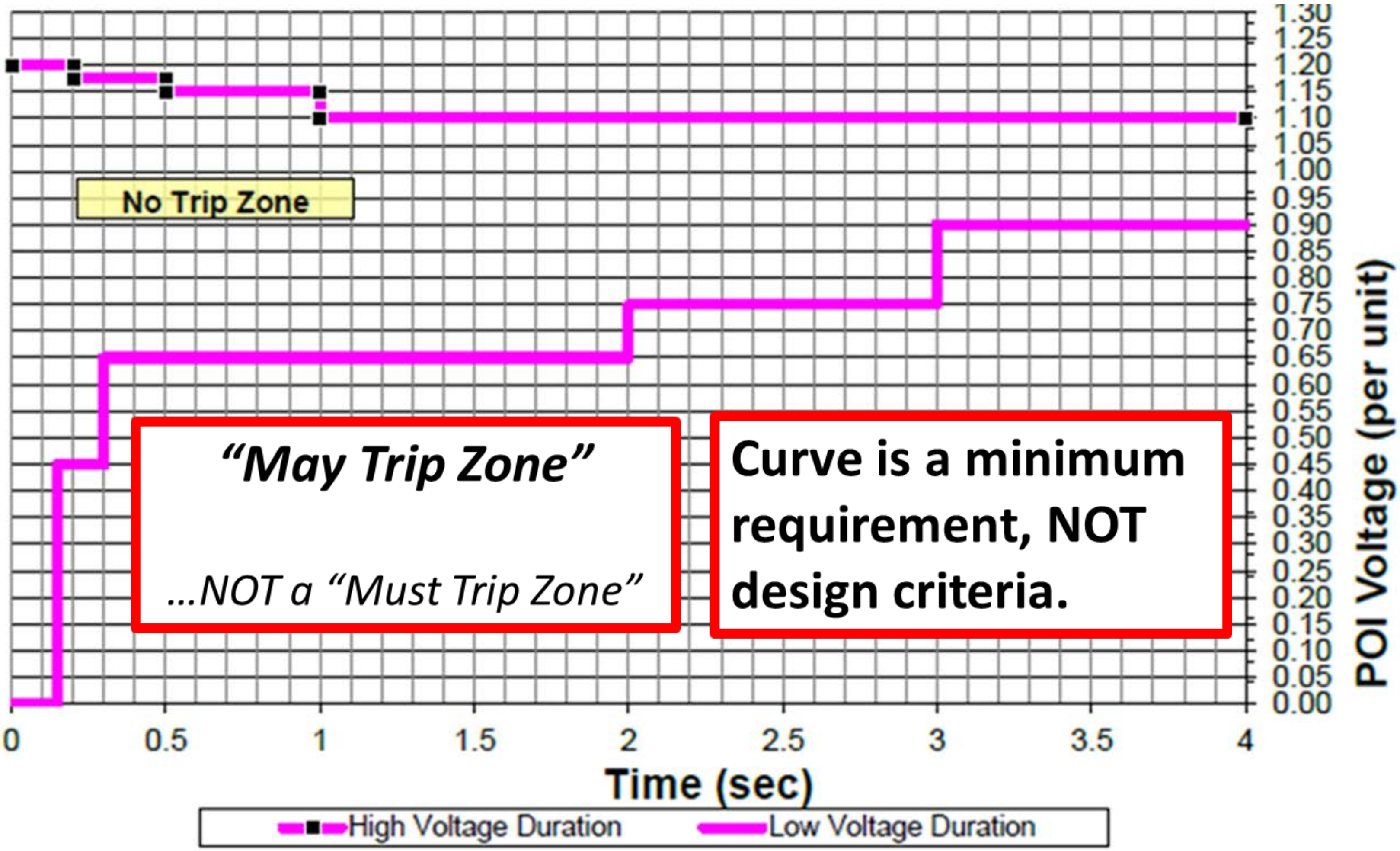
- During ride-through conditions, the inverter controls its output and ignores signals sent by the plant-level controller. After voltage recovers and the inverter enters a normal operating range, it again responds to signals from the plant controller. The plant controller then applies its ramp rate limits to the remaining recovery of current injections, restraining the inverter from recovering quickly to its pre-disturbance current injection.
- Active current injection should not be restricted by a plant-level controller or other slow ramp rate limits.

Canyon 2 Fire: Key Finding #4

Interpretation of PRC-024-2 Voltage Ride-Through Curve

- Many inverters are set to trip when outside of the PRC-024-2 voltage ride-through curve. The curve is often used for inverter protective trip settings rather than setting the protection to the widest extent possible while still protecting the equipment.
- The region outside of the PRC-024-2 voltage ride-through curve is being **<u>misinterpreted</u>** as a “must trip” rather than “may trip”.
- Voltage protection functions in the inverters should be set based on physical equipment limitations to protect the inverter itself and should not be set based solely on the PRC-024-2 voltage ride-through characteristic.

Canyon 2 Fire: Key Finding #4



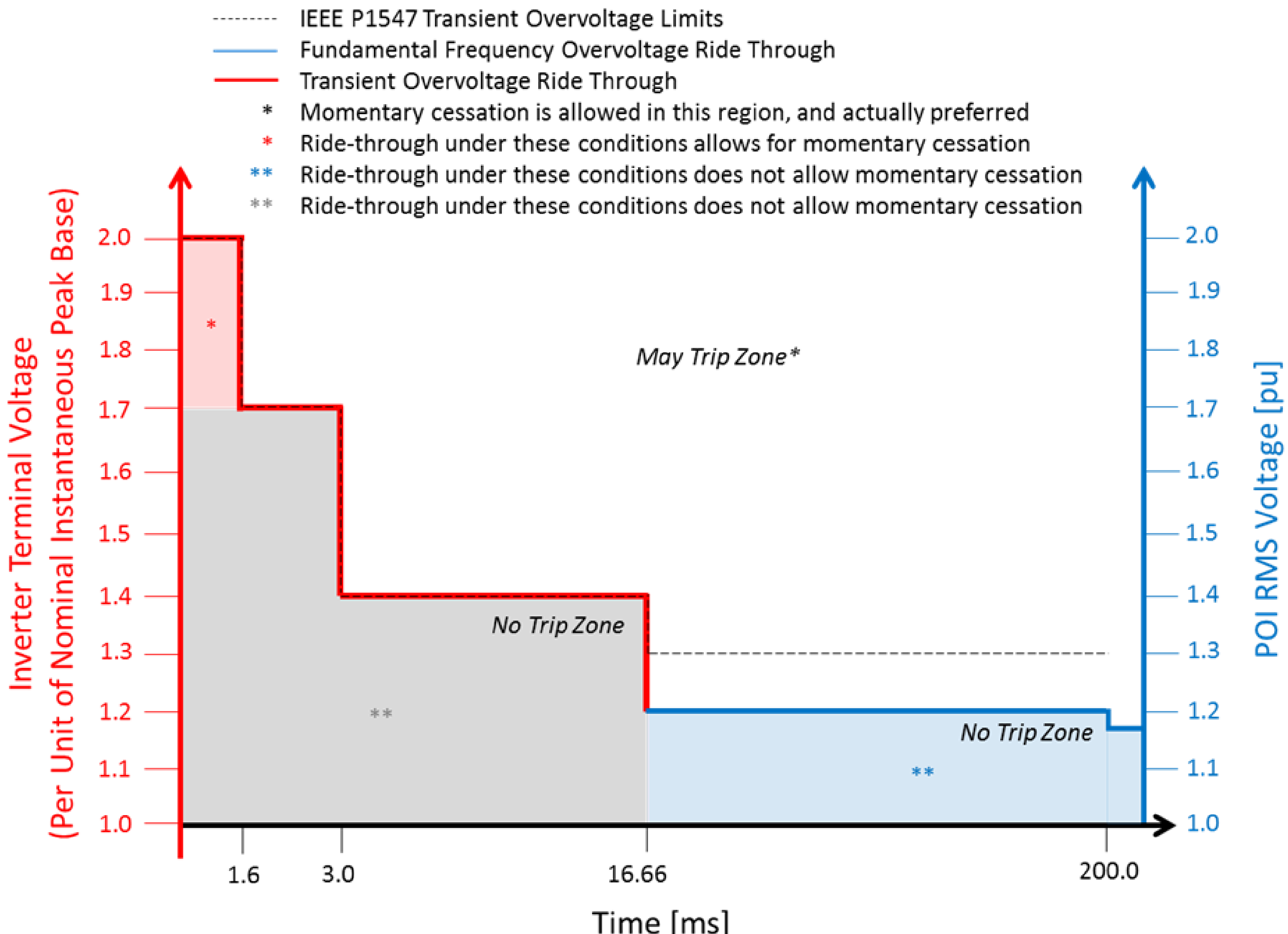
Canyon 2 Fire: Key Finding #5

Instantaneous Voltage Tripping and Measurement Filtering

- A large percentage of existing inverters on the BPS are configured to trip using instantaneous overvoltage protection, based on the PRC-024-2 high voltage ride-through curve, and do not filter out voltage transients. Any instantaneous, sub-cycle transient overvoltage may trip the inverter off-line, making these resources susceptible to tripping on transients caused by faults and other switching actions.
- Inverter protective functions should use a filtered, fundamental frequency voltage input for overvoltage protection when compared with the PRC-024-2 ride-through curve.

Canyon 2 Fire: Key Finding #5

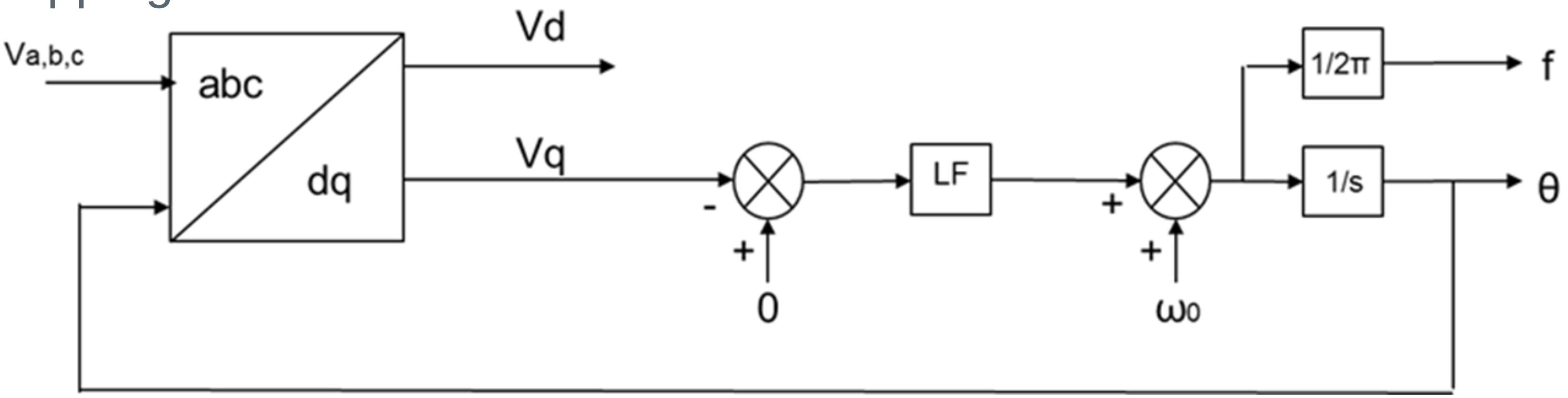
IRPTF HVRT Recommendation



Canyon 2 Fire: Key Finding #6

Phase Lock Loop Synchronization Issues

- Grid voltage phase jumps occur (during faults, breaker operations, etc.)
- Inverter PLLs should be robust to withstand BPS phase jumps
- Should not result in inverter tripping or momentary cessation
- Advanced controls should enable “PLL ride-through” rather than tripping



Canyon 2 Fire: Key Finding #7

DC Reverse Current Tripping

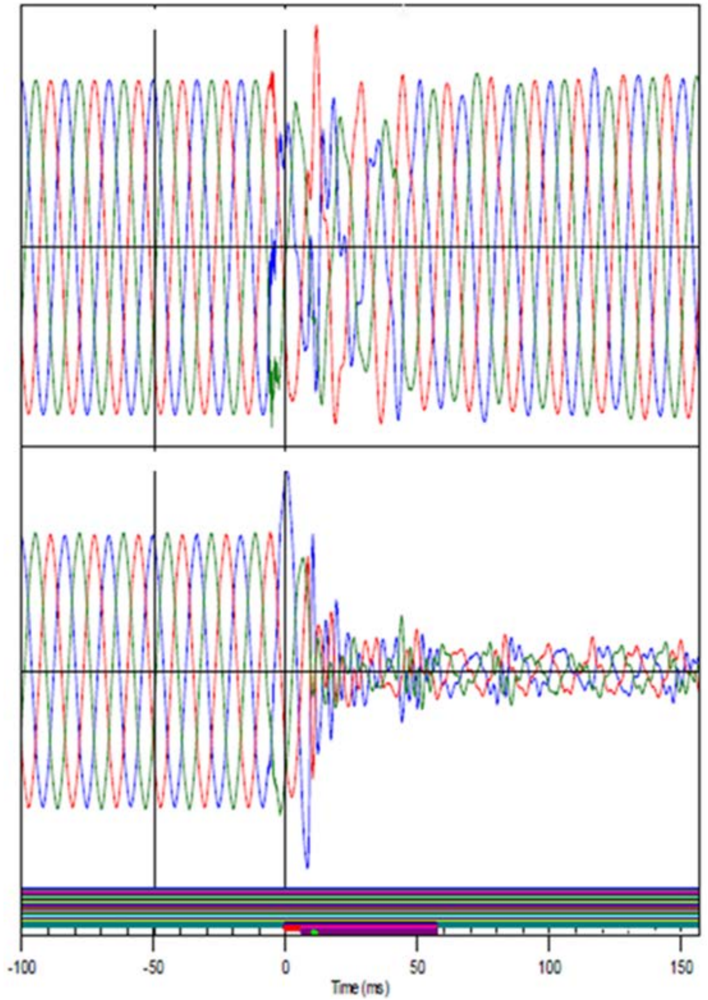
- One inverter manufacturer reported fault codes for dc reverse current, which caused protective action to open the inverter primary circuit breaker.
  - Caused resources to remain off-line for average 81 minutes, manual reset.
- GOs should coordinate with their inverter manufacturers to ensure that dc reverse current detection and protection are set to avoid tripping for dc reverse currents that could result during sub-cycle transient overvoltage conditions since these are not likely to damage any equipment in the plant. Mitigating steps may include:
  - Increasing magnitude settings to align with the ratings of the equipment.
  - Implementing a short duration to the dc reverse current protection before sending the trip command.

Canyon 2 Fire: Key Finding #8

Transient Interactions and Ride-Through Considerations

- There appears to be an interrelationship between in-plant shunt compensation, sub-cycle transient overvoltage, and momentary cessation that results in inverter tripping. The causes and effects are not well understood and require detailed Electromagnetic Transient (EMT) simulation studies

- EMT studies should be performed by affected GOPs, in coordination with their TO to better understand the cause of transient overvoltages resulting in inverter tripping. These studies should identify why observed inverter terminal voltages are higher than the voltage at the point of measurement and any protection coordination needed to ride through these voltage conditions.



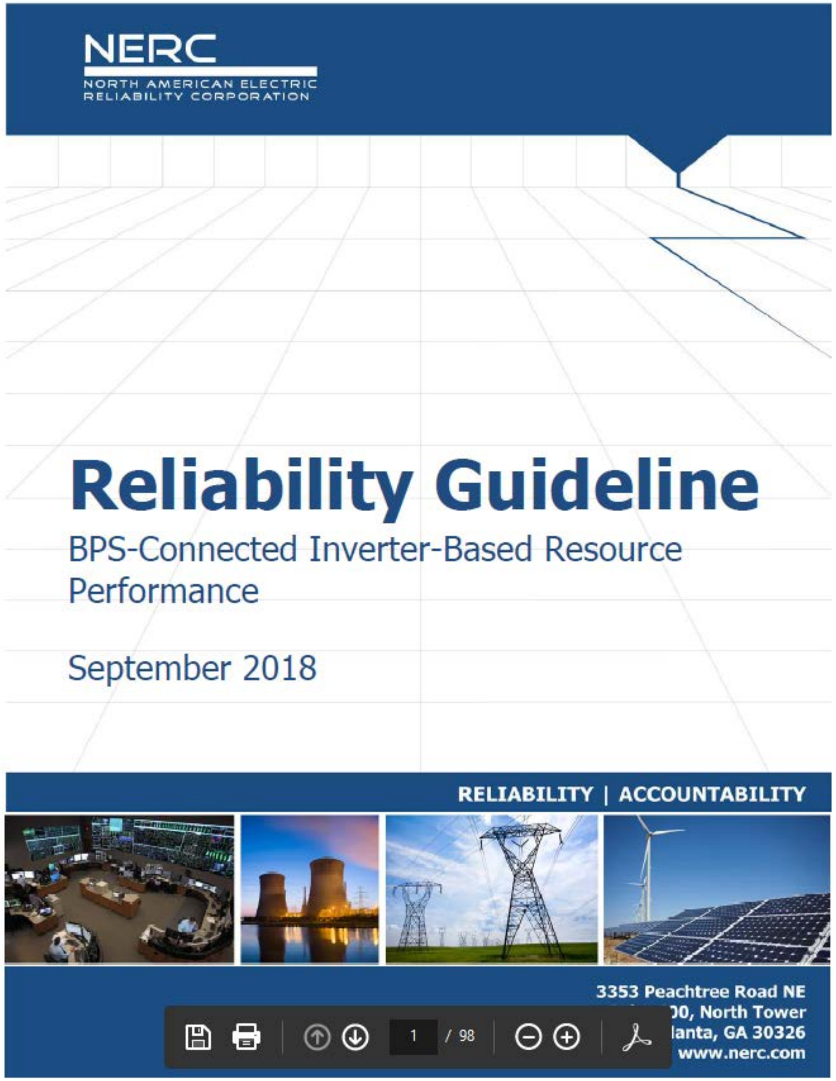
Canyon 2 Fire: Outcomes

- NERC Alert II
  - ERCOT study results presented at January 2019 ROS: http://www.ercot.com/content/wcm/key_documents_lists/165170/07.__MC_January_ROS.PPTX
- Reliability Guideline Recommendations
- PRC-024-2 Whitepaper and Standards Authorization Request
  - NERC Project 2018-04
- Event report:

  https://www.nerc.com/pa/rrm/ea/October%209%202017%20Canyon%202%20Fire%20Disturbance%20Report/900%20MW%20Solar%20Photovoltaic%20Resource%20Interruption%20Disturbance%20Report.pdf

IRPTF Accomplishments

- Reliability Guideline*
- NERC Alerts
- PRC-024 SAR
- PRC-019 SAR and Implementation Guidance Document Review
- Modeling and Simulations
- Workshop



*https://www.nerc.com/comm/PC_Reliability_Guidelines_DL/Inverter-Based_Resource_Performance_Guideline.pdf

IRPTF Ongoing Work

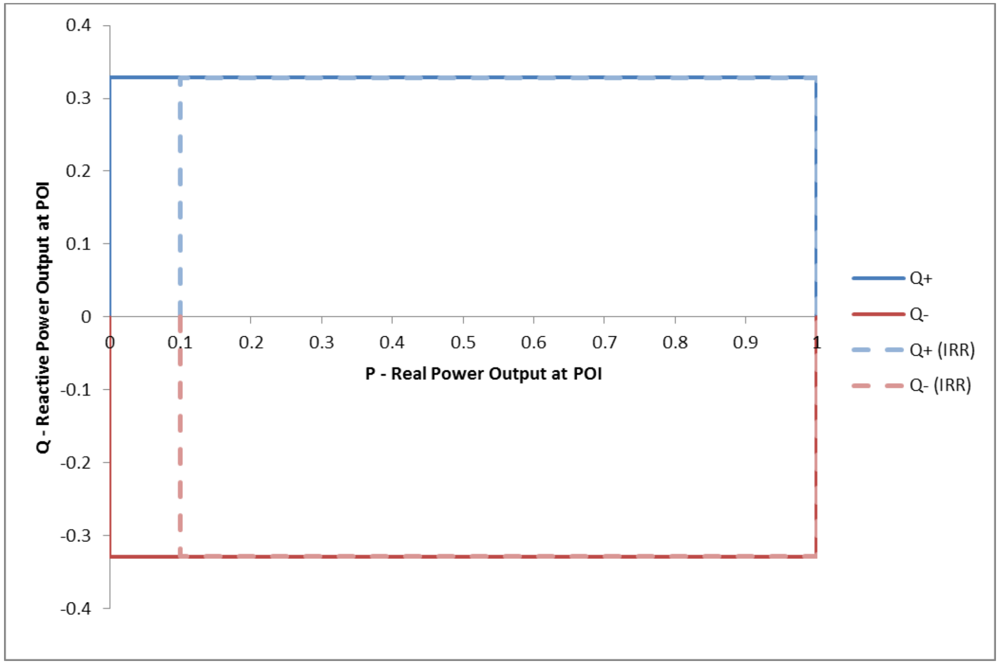
- Reliability Guideline : Recommended Improvements to Interconnection Agreements for Inverter-Based Resources
- White Paper: Terminology for Fast Frequency Response Test and Low Inertia Systems – NERC IRPTF Perspectives
- Monitor and Support IEEE P2800: Standard for Interconnection and Interoperability of Inverter-Based Resources Interconnecting with Associated Transmission Electric Power Systems
- Comprehensive review of NERC Reliability Standards
- NERC Alert II follow-up

2. Review Existing ERCOT Protocol/Guides

- Reactive Capability Requirements (Nodal Protocol (NP) 3.15 and Nodal Operating Guide (NOG) 3.3.2)
- Voltage Ride-Through and Momentary Cessation (NOG 2.9)
- Reactive and AVR Testing (NOG 2.2.5 and 3.3.2.2)
- Voltage Droop and Deadband (NOG 2.7.3.5(4))
- Frequency Ride-Through (NOG 2.6.2)
- Frequency Droop and Deadband (NOG 2.2.7)
- Frequency Response Testing (NOG 8(C))
- Ramp Rate Limitation (NP 6.5.7.10)

Reactive Capability Requirements

- Resources must have sufficient reactive capability to provide 0.95 power factor leading and lagging relative to the maximum net real power deliverable to the POI
- Must be provided at all real power outputs from 10% of Pmax to Pmax



Reactive Capability Requirements (continued)

- Required reactive capability must be provided at any POI voltage setpoint from 0.95pu – 1.05pu
- Required reactive capability must be provided by dynamic reactive sources
  - Inverters, SVCs, STATCOMS, etc.
  - Fast-acting switched shunts may be used to compensate for collector system losses and ensure that the inherent dynamic capability of the inverters and auxiliary dynamic reactive devices is deliverable to the POI
- Reactive capability is evaluated via the Reactive Study and later verified through reactive and AVR testing

Reactive Capability Reporting

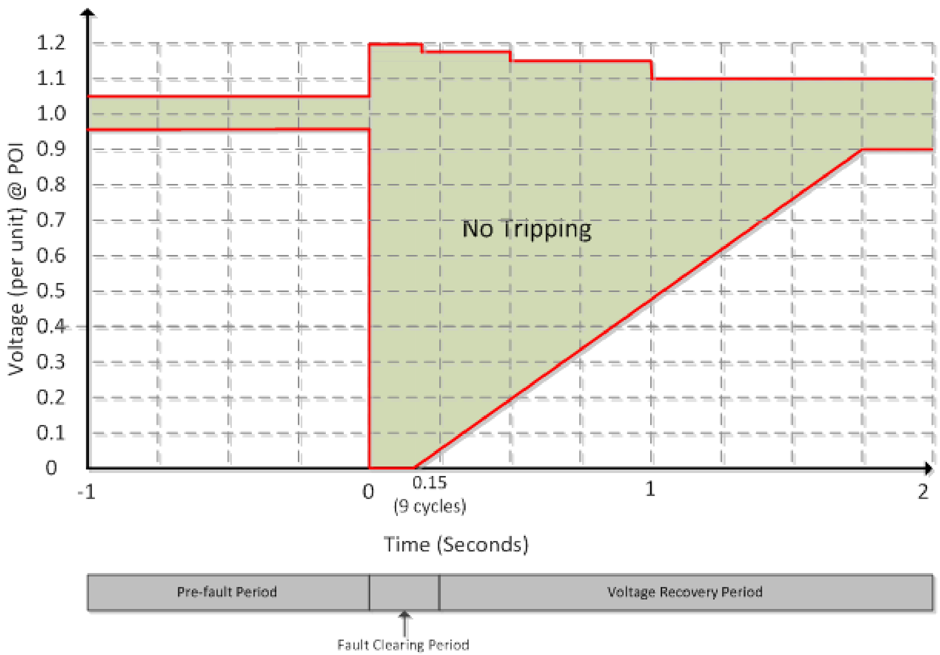
- Reactive capability data reported in the RARF and CURL points reported in NDCRC should represent the gross maximum physical capability of a resource to produce reactive power at each level of real power output, adjusted to reflect the effects of any physical limitations
- Inverter-based resources should not have artificial (non-physical) limits imposed to limit reactive power output
  - This expectation is supported by the NERC IRPTF Guideline

VRT Capability and Momentary Cessation

- ERCOT interprets “voltage ride-through capability” to mean that a resource maintains its real power output post-disturbance
  - The NERC IRPTF Guideline includes specific guidelines for real power recovery
- Nodal Operating Guide Section 2.9(2) forbids the use of momentary cessation to ride through an event
- “…each Generation Resource **shall not**, during and following a transient voltage disturbance, **cease providing real or reactive power** except to the extent needed to provide frequency support or aid in voltage recovery.”

Voltage Ride-Through

- ERCOT expects that resources demonstrate dynamic reactive capability and evidence of appropriate AVR response during VRT tests
- The area outside the “No Trip Zone” should not be considered a “Must Trip Zone”



Reactive and AVR Testing

- Reactive tests, AVR tests, and VSS evaluations are considered together to determine whether or not a resource demonstrates required reactive power control
- Questions arise if:
  - A resource demonstrates reactive capability significantly greater than what was reported in the RARF or NDCRC
  - There is evidence that the power plant controller is being used to artificially limit reactive capability
  - Reported and telemetered values do not match
- If necessary, the RARF should be updated to reflect reactive capability verified via testing

Reactive Testing for IRR

- Required tests for Intermittent Renewable Resources (IRR) are:
  - Lagging Test 1 (15 minute test)
    - IRR test at or above 60% of their HSL
    - Test acceptance criteria – achieve at least 90% of CURL
  - Lagging Test 2 (1 hour test)
    - IRR test with at least 90% of photovoltaic inverters or wind turbines on-line
    - Test acceptance criteria – achieve at least 50% of CURL
  - Leading Test 1 (15 minute test)
    - IRR units test at or below 60% of their HSL
    - Test acceptance criteria – achieve at least 90% of CURL

Reactive Testing for BESS

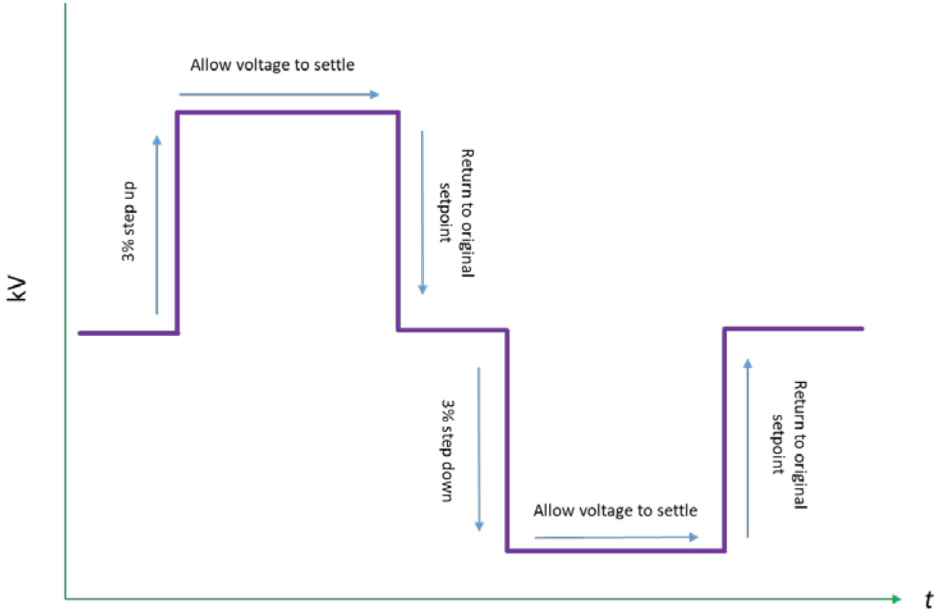
- Battery Energy Storage Systems (BESS) are not considered IRR, but must be evaluated similarly due to their inverter-based nature
- The energy-limited nature of BESS may require ERCOT to exercise some discretion in evaluation reactive tests
  - For example, some BESS may struggle to maintain output for the hour-long lagging test

AVR Testing

- Nodal Operating Guide Section 2.2.5(2)(a) requires that any reactive devices needed to meet VSS requirements are included in the AVR control system and that all devices included in the AVR control system are included in the AVR test
  - This includes any auxiliary dynamic reactive devices, and fast-acting switched shunts need to compensate for collector system losses

AVR Testing

- AVR tests should be coordinated with ERCOT and the TSP
- Data should be reported in 4-s intervals (or smaller)
- A 3% step is recommended, but exceptions can be accommodated if the resulting voltage would exceed limits or the TSP has placed additional restrictions on the setpoint



AVR Testing

- ERCOT expects to see full dynamic response within 30s and full AVR response, including switched shunts in less than 1min
  - The 30s dynamic response expectation is in line with recommendations in the NERC IRPTF Guideline
- If the voltage setpoint cannot be achieved, the resource must have reached its reactive limit
- Some overshoot is acceptable, but it should not be excessive or sustained
- Any voltage deadband employed is considered when AVR tests are evaluated

Voltage Droop and Deadband

- Voltage droop and deadband should be coordinated with neighboring resources to avoid control system conflicts
- Nodal Operating Guide Section 2.7.3.5(4) requires that a resource be at its maximum reactive capability when the POI voltage is not within 2% of the voltage setpoint
  - As such, the sum of the voltage droop (%) and voltage deadband (%) should not exceed 2%

Frequency Ride-Through

- The requirements for under-frequency and over-frequency relay settings in Nodal Operating Guide Section 2.6.2 correspond to those in PRC-024-2
- The requirement is intended to define “No Trip” boundaries, not “Must Trip” boundaries
- IRPTF Guideline recommendations:
  – The frequency used for “instantaneous” trip settings should be calculated over a time window (e.g. six cycles)
  – Frequency trip settings should be set as wide as possible while ensuring that equipment and personnel are protected

Frequency Droop and Deadband

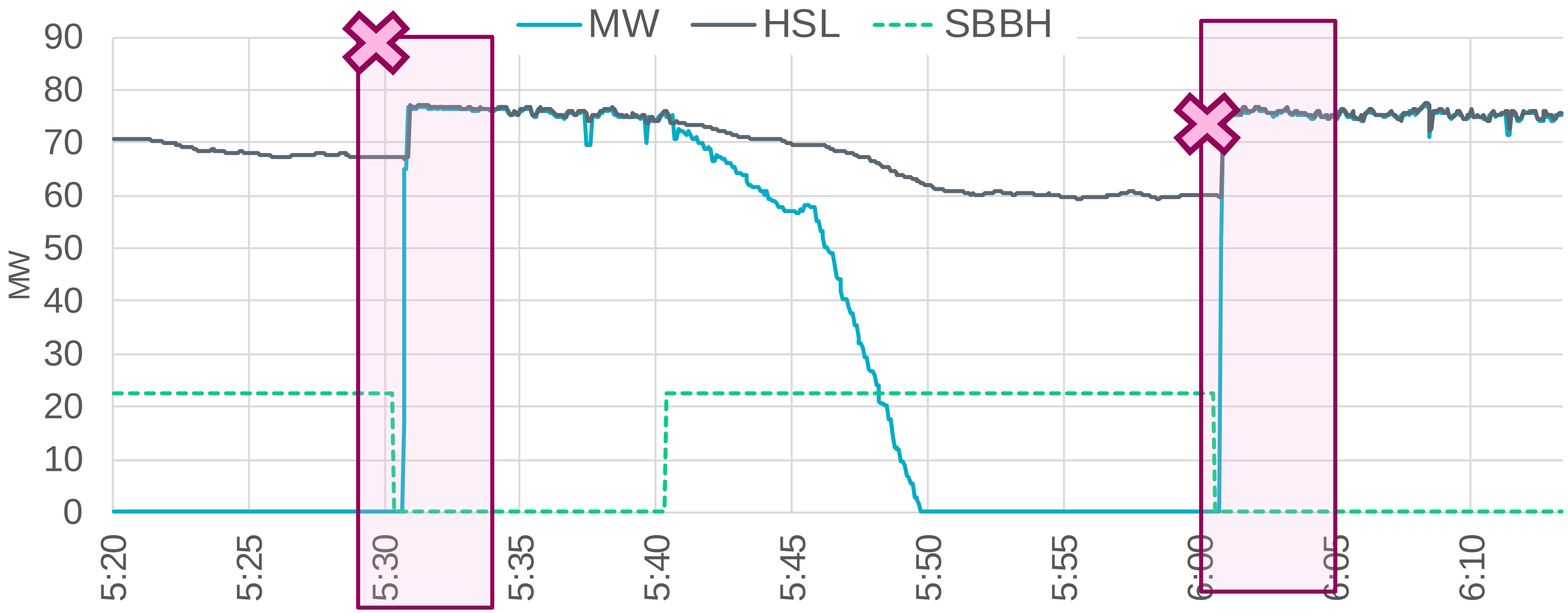
- Nodal Operating Guide Section 2.2.7(3) defines maximum frequency droop and deadband settings for resources
- The maximum frequency deadband for inverter-based resources is +/- 0.017 Hz
- The maximum frequency droop for inverter-based resources is 5%

Frequency Response Testing

- Test procedures for frequency response testing are found in Nodal Operating Guide Section 8(C)
- Frequency response test data is submitted via NDCRC and is automatically evaluated
- Frequency offsets of +/- 0.2 Hz are used
- Tests are considered successful when at least 70% of the calculated MW contribution is delivered within 16s and the response is maintained for an additional 30s
  - MW Contribution = (Gain MW for 0.1 Hz)*(10)*(Frequency Offset)
  - Gain MW for 0.1Hz = P / [(Droop*60 – Deadband)*10]

Ramp Rate Limitations

- Each IRR that is part of a Standard Generation Interconnection Agreement (SGIA) signed on or after January 1, 2009 shall limit its ramp rate to 20% per minute of its nameplate rating (MWs) as registered with ERCOT when responding to or released from an ERCOT deployment.



Discussions

3.1 Voltage Support and Coordination

- Voltage droop and deadband
- Shunt device switching in AVR control schemes
- Reactive performance at low real power output

Voltage Droop and Deadband

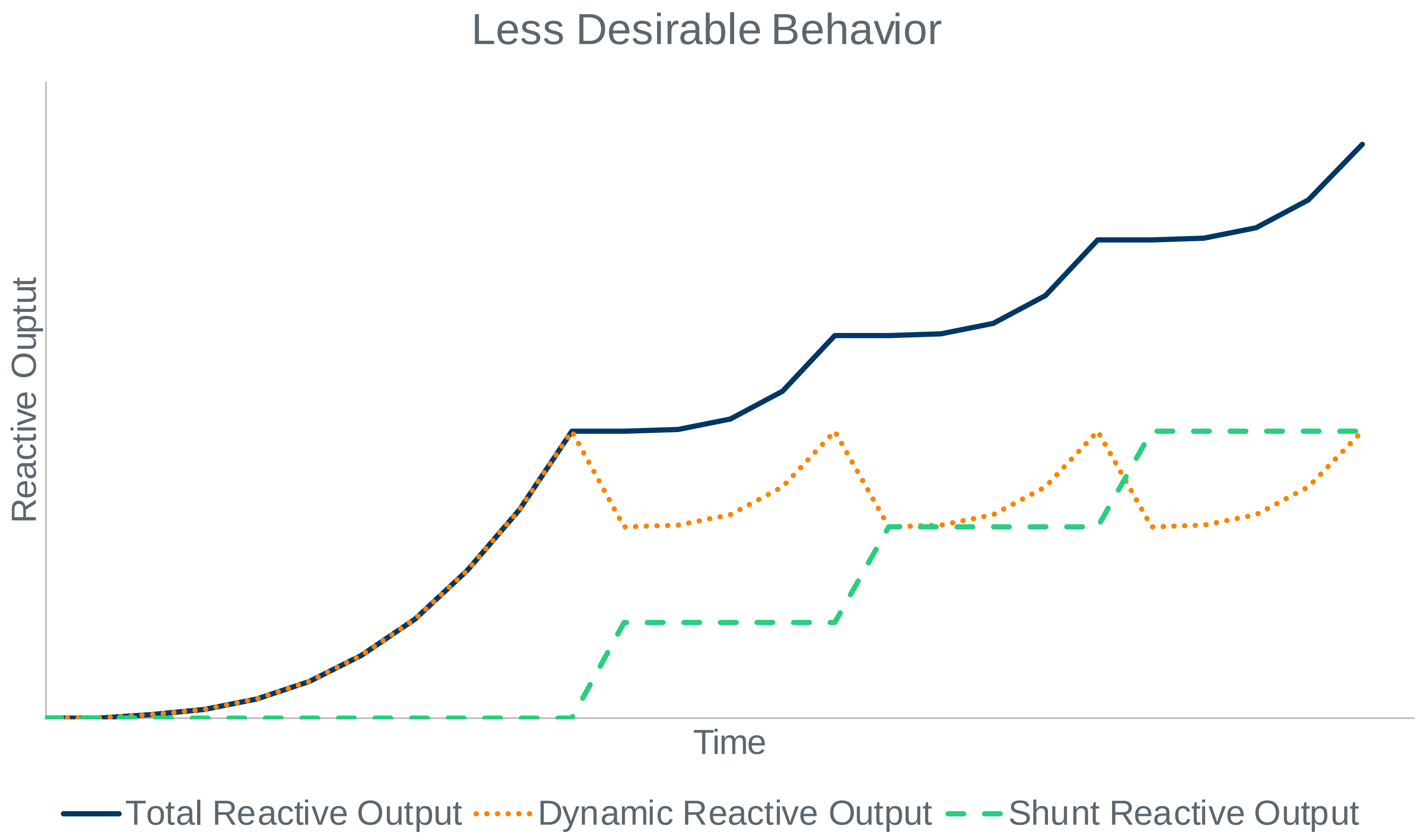
- Clarity is needed for voltage droop and deadband definition and recommendations / requirements
- ERCOT intends to submit a NOGRR that would change the 2% tolerance band that current voltage droop and deadband guidance is based on
  - Tolerance bands would vary by voltage class
- Voltage droop and deadband recommendations / requirements could be linked to these updated tolerance bands
  - Deviations from recommendations / requirements may be needed in certain areas, but would require ERCOT / TSP approval

Shunt Device Switching in AVR Controls

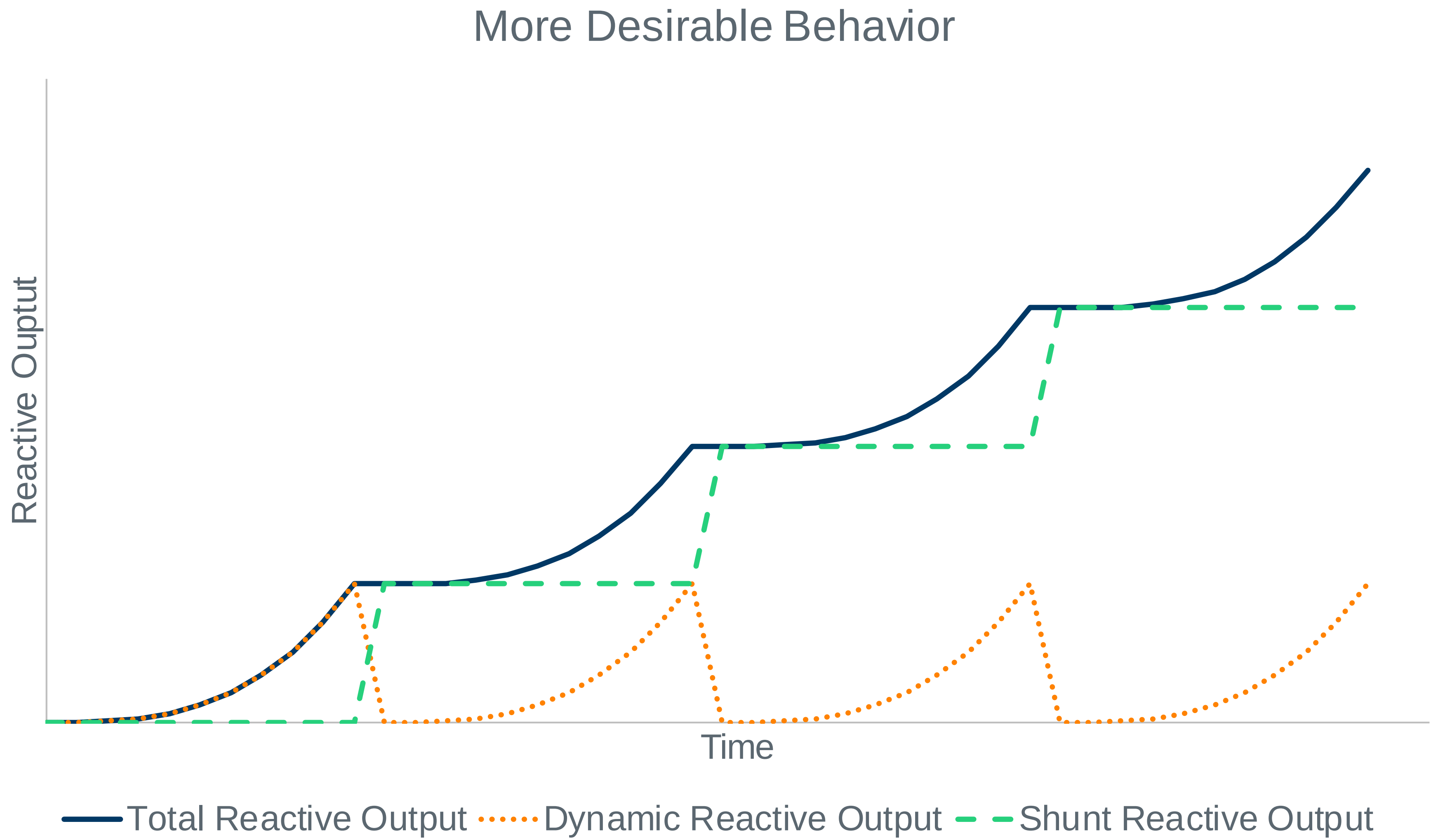
- There have been some operational issues associated with shunt device switching schemes as part of AVR control systems
  - Some switching schemes can cause inverters to trip offline for voltage protection

- Shunt device switching schemes should maximize the amount of dynamic reactive capability available from inverters
  - Similar to what is done now with TSP-owned reactive devices

Shunt Device Switching in AVR Controls



Shunt Device Switching in AVR Controls

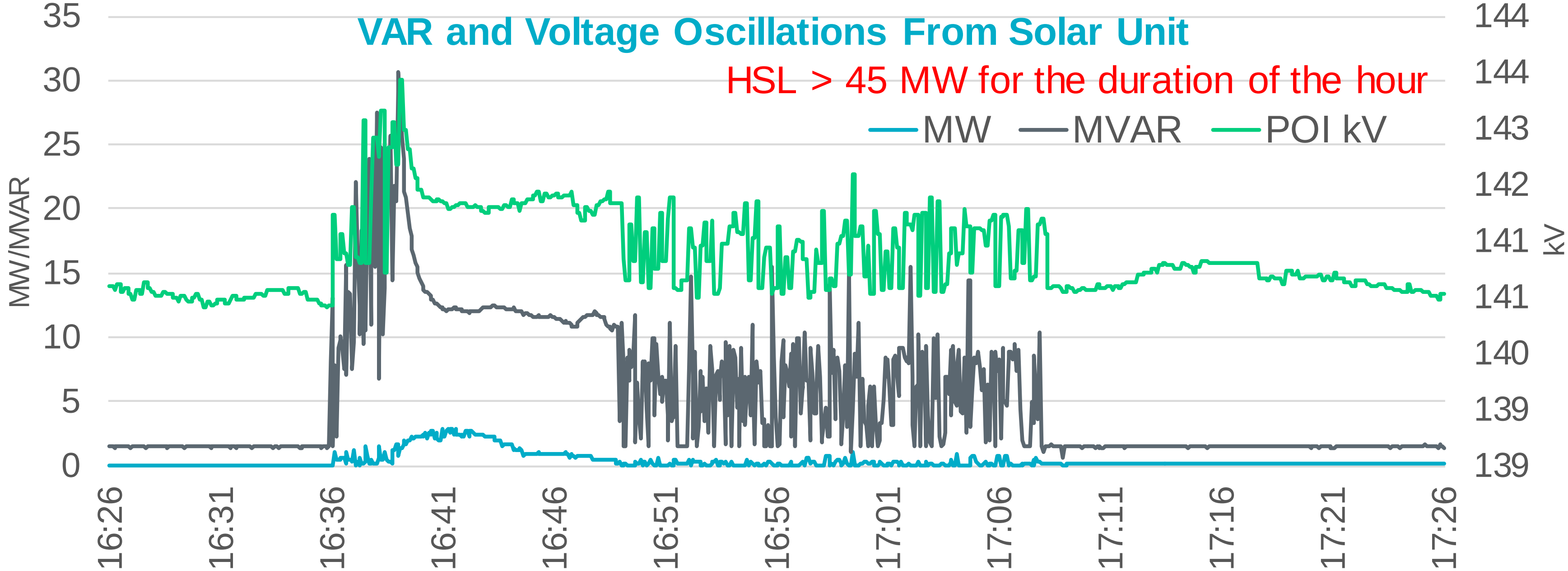


Reactive Performance at Low Real Power Output

- Inverter-based resources can have high reactive power capability at real power outputs less than 10% of Pmax
  - ERCOT expects that such capability is reported on the RARF
- Existing reactive tests are generally not performed at such low real power outputs
  - Testing to verify reactive power capability at low real power output may be desirable
  - Sometimes inverter-based resources are the only resources in an area that can provide reactive support

Operational Experience and Challenges

- IBRs are required to provide voltage support when output is greater than 10% of nameplate capacity.
- When curtailed, inverters may toggle between online and offline states as curtailment transitions across the inverter's minimum MW limit. As a result, some inverters inadvertently cause VAR and voltage oscillations as they toggle across the 10% limit



Discussions/Next Steps

3.2 Momentary Cessation

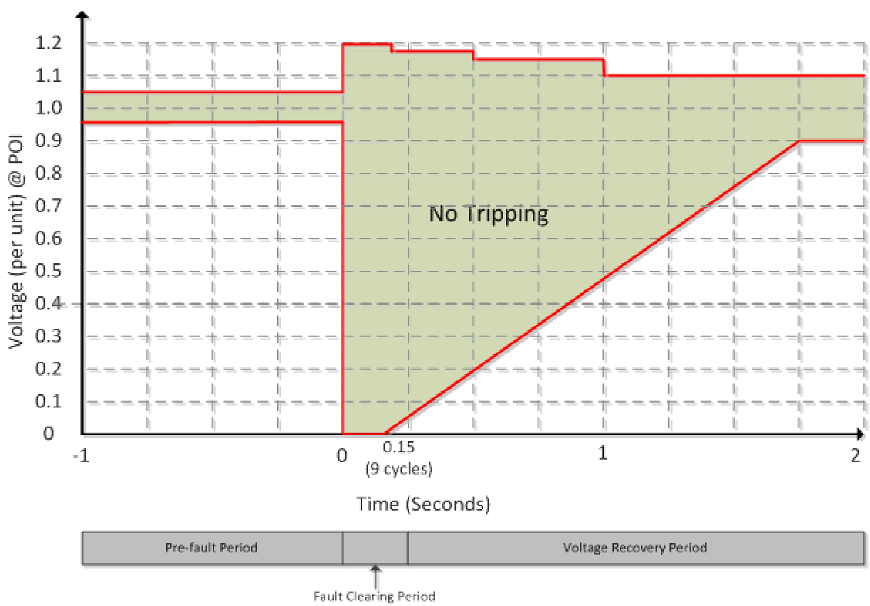
- ERCOT Nodal Operating Guide 2.9 (2)

  … each Generation Resource **shall not**, during and following a transient voltage disturbance, **cease providing** real or reactive power except to the extent needed to provide frequency support or aid in voltage recovery.

- Clarification/Revision Considerations
  - Adopt NERC Momentary Cessation terminology
  - Present and publish the performance expectation
    - LVRT: may be acceptable to allow MW reduction for more Q injection to support voltage recovery but should have a timely MW recovery after fault clearing
    - HVRT: should remain the pre-fault MW level

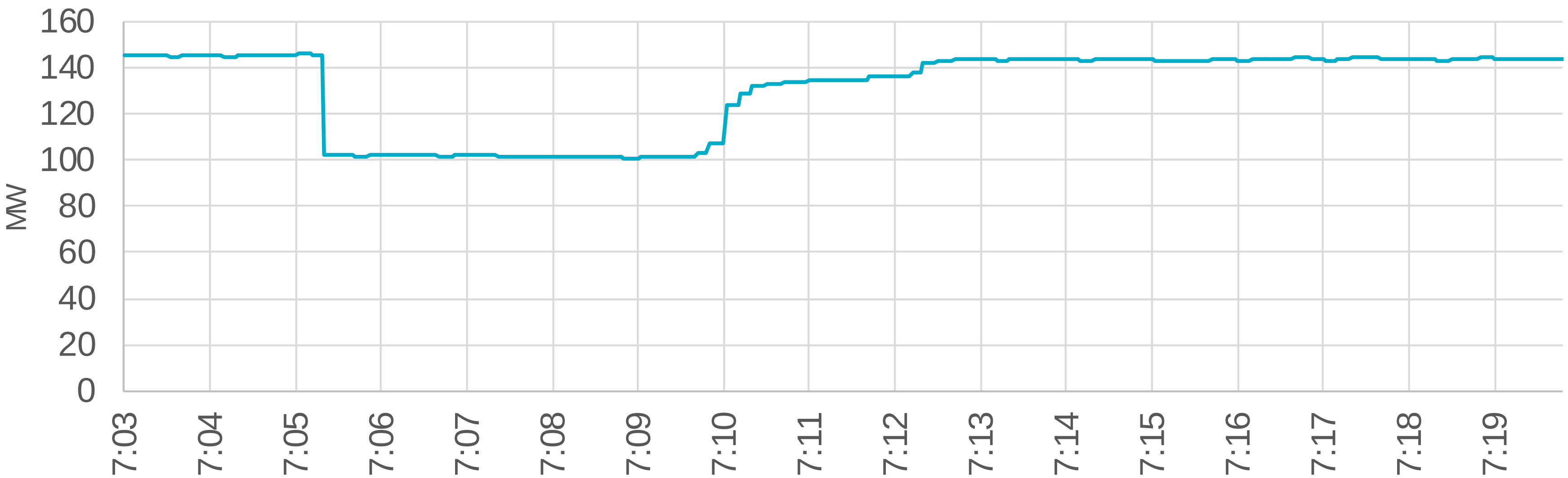
ERCOT Voltage Ride Through

- ERCOT Nodal Operating Guide 2.9.1 Voltage Ride Through Boundaries for IRRs.
- Clarification/Expectation:
  - IRR shall remain connected to the system even when the voltage profile is outside the No-Trip zone as long as there is no concern of facility limitation.



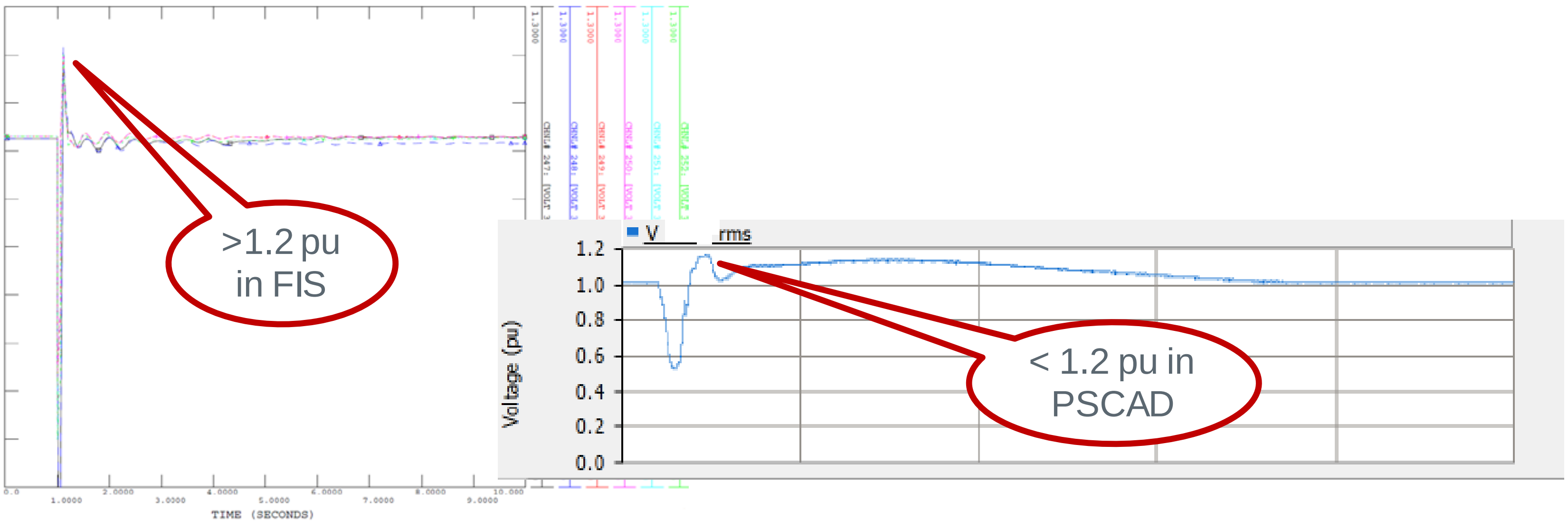
Challenges of Partial Trip During Faults

- A single line to ground fault on a 138 kV transmission line, a wind farm that experienced loss of 18 out of 61 turbines.
- The preliminary cause is the crowbar failure, which is the critical component for WGRs' voltage ride through capability.
- Awareness of critical component failure/maintenance is necessary because it could affect the responses and support of the generation facilities.



ERCOT Voltage Ride Through

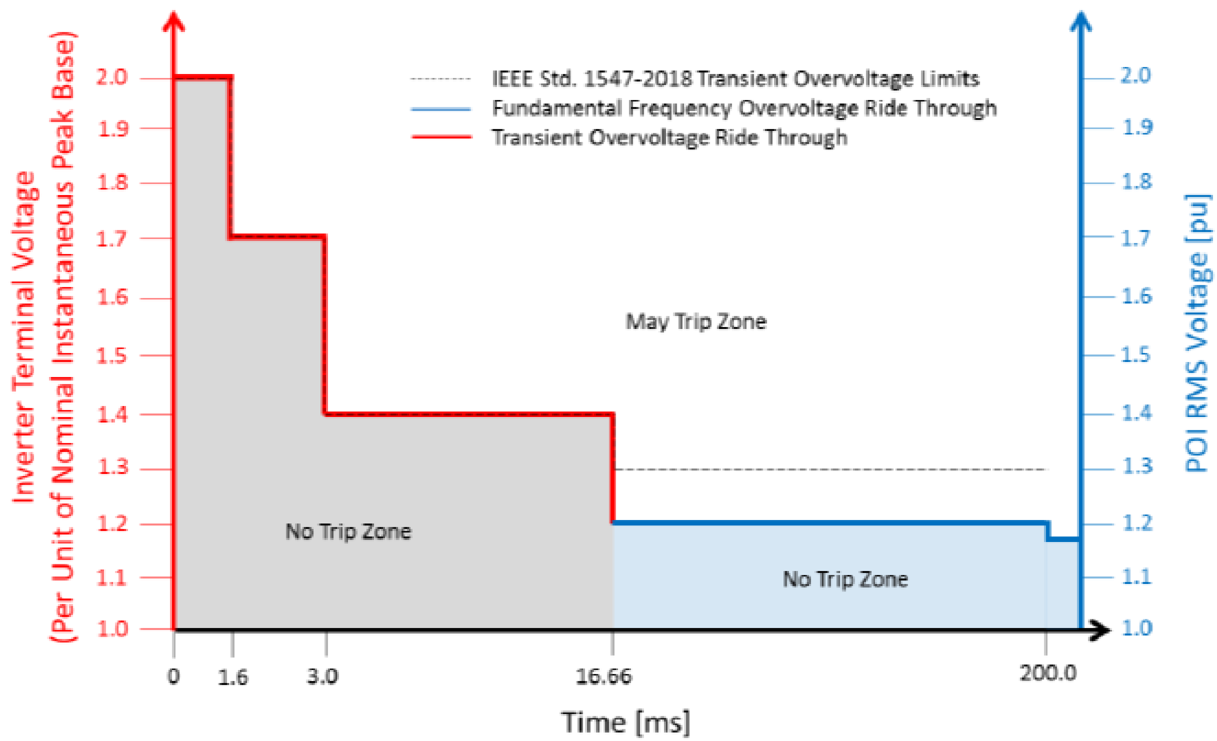
- Observations: increasing transient overvoltage tripped observed in the interconnection dynamic studies
  - Are they real or just numerical issues?
  - Acceptable to allow gen trip due to transient overvoltage voltage?



*Examples are only for illustration purposes. They are not representative of any actual project

ERCOT Voltage Ride Through

- Clarification/Revision Considerations
  - Require PSCAD study in FIS
  - Consider transient overvoltage ride through requirement



*NERC Reliability Guideline: BPS-Connected Inverter-Based Resource Performance

Discussions/Next Steps

3.3 Voltage Support Capability under Low/Zero Output

Existing Voltage Support Service Requirement

Protocol Section 3.15(3)(c):

“*…For Intermittent Renewable Resources (IRRs), the Reactive Power requirements shall be available at all MW output levels at or above 10% of the IRR’s nameplate capacity. When an IRR is operating below 10% of its nameplate capacity and is unable to support voltage at the POI, ERCOT may require an IRR to disconnect from the ERCOT System for purposes of maintaining reliability…*”

Challenges with Existing Requirements

1. Collector system charging causes MVAr injection at low/zero resource output
   – Operational experience has also indicated poor voltage control for resources at low MW injection levels due to designing to ERCOT’s “10% rule”

2. Many IBRs are located in West Texas where voltage support is needed 24/7
   – Operators can’t RUC a solar PV plant at night
   – Example: Each 250 MVAR STATCOM in the Far West Texas 2 Project was estimated to cost $35M

Currently Available Technology

- Solar PV inverters can provide dynamic reactive support (similar to STATCOMs) at night if configured to do so at the time of plant design
- Battery inverters can also provide this reactive response during charging or when idle
- Newer wind turbines can provide a similar response at zero MW output (no wind)
- Inverters providing reactive support or sitting in standby mode will consume a relatively small amount of power
  - A STATCOM would be expected to consume a similar amount

The Idea

- Change requirements such that inverter-based resources provide voltage support service below 10% output (down to and including 0 MW)
- This may mitigate the need for future reactive device transmission projects, saving consumers money
- Also, will resolve observed operational issues

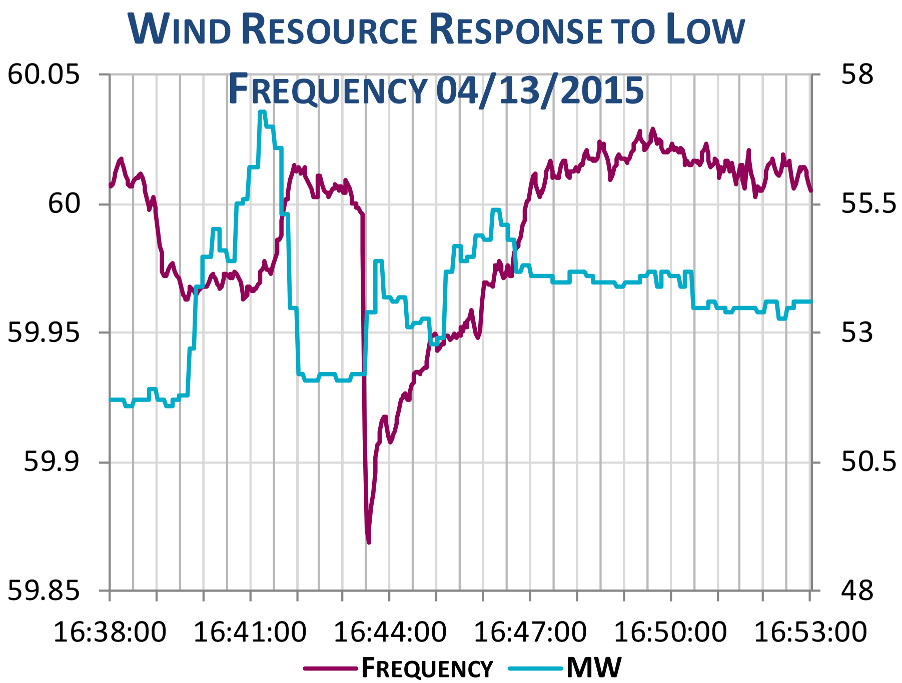
Discussions/Next Steps

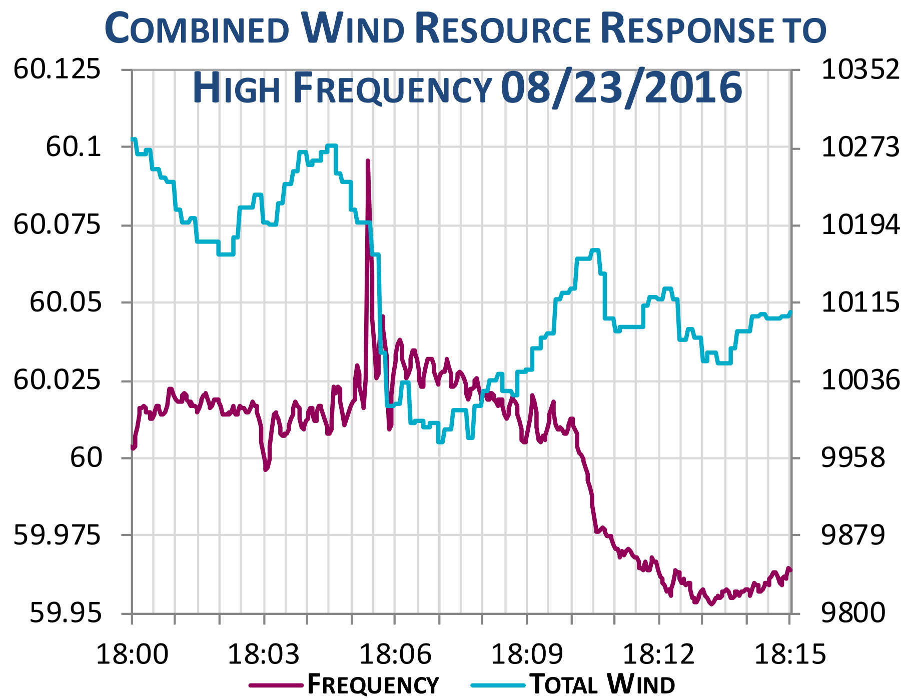
3.4 Frequency Ride Through

- Nodal Operating Guide Section 2.6.2 outline “no trip” boundaries for under-frequency and over-frequency relays that are applicable to all generators
  - While the settings in Section 2.6.2 correspond to those specified in PRC-024-2, generators are not limited by these settings and may deviate in order to protect the resource from potentially damaging conditions.
  - For IBRs, Frequency/time zone combinations that fall outside the “no trip” boundaries in Section 2.6.2 should not be treated as “must trip”.

Primary Frequency Response

- IBRs operating in ERCOT are required to have the capability to provide primary frequency response (PFR) and deliver that primary frequency response to the grid when they have frequency responsive headroom.



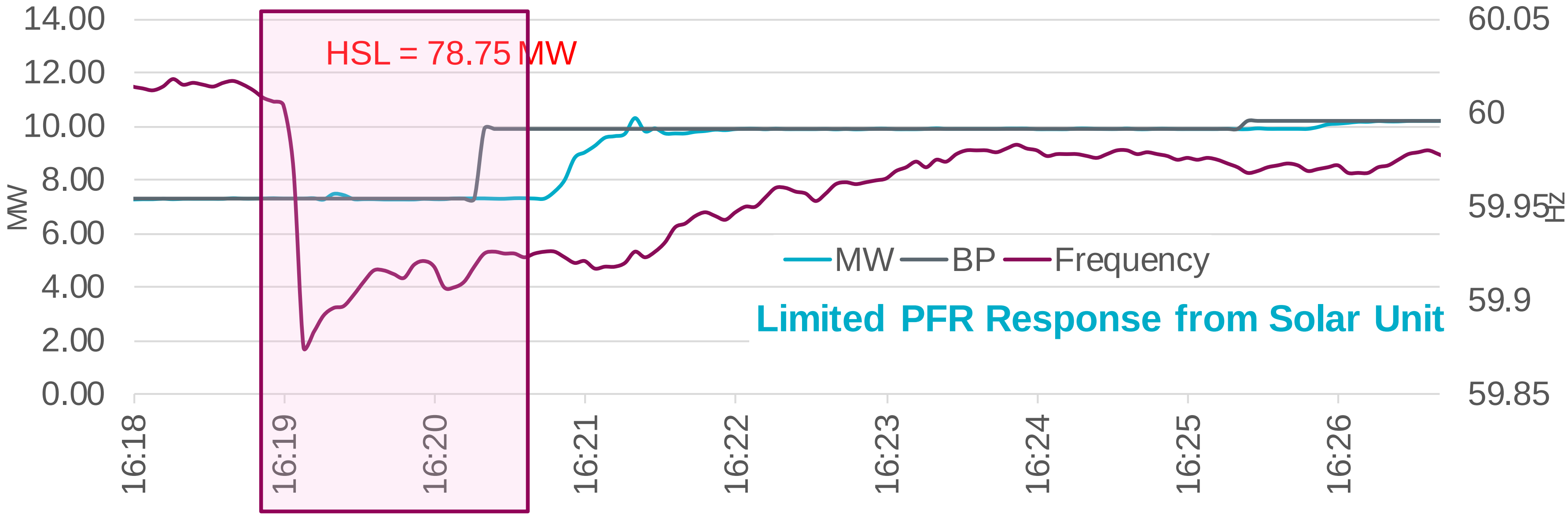


Frequency Measurement

- ERCOT rules do not have specific criteria for frequency measurement. It is expected that the IBRs have the ability to reliably measure frequency and not trip due to improper measurements.
  - As an example methodology recommended in the IRPFT Frequency used for "instantaneous" trip settings may be calculated over a time window to avoid false positive trips.
- IBRs should be able to ride through and not trip for phase jumps or other grid disturbances when calculated frequency is affected but grid frequency is within the ride-through curves of PRC-024-2.
  - Note, testing the inverter's capability to ride through these types of disturbances is not part of the performance-based standard used by NERC.
- IBRs do not have an equipment limitation or need to trip on high rate-of-change-of-frequency (ROCOF).
  - ROCOF relays should not be used for inverter-based resources connected to the BPS and should be disabled in the inverter.
- Phase lock loop loss of synchronism should not result in inverter trip.

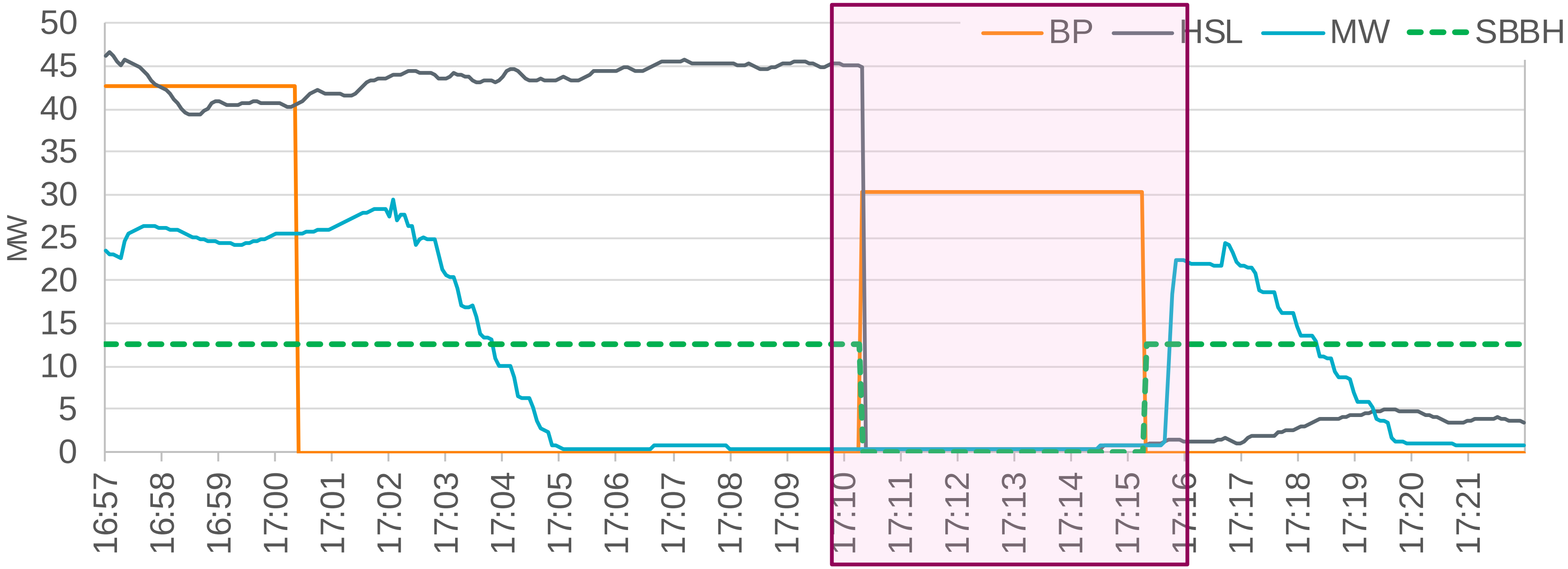
Operational Experience and Challenges

- IBRs that are curtailed to 0 MW or close to 0 MW are expected to be online for the purposes of SCED dispatch and to provide primary frequency response.
- However, some inverters have a minimum MW limit to remain online.
- Based on how long these resources have been operating below the minimum MW limit, some inverters may go into standby mode or external stop.
- As a result, the resource/inverters are unable to provide PFR contrary to expectation.



Operational Experience and Challenges

- Furthermore, certain inverters have built-in timed protection settings before which the inverter cannot be brought online.



Discussions/Next Steps

3.5 Dynamic Performance Requirements for Active and Reactive Power

- IBR performance is mainly driven by controllers and settings. Developers, Resource Entities, and vendors have asked for the dynamic performance requirements for their controller settings.

- Dynamic performance characteristics can be defined by the followings:
    1. Delay
    2. Rising Time
    3. Settling Time
    4. Settling Band
    5. Overshoot

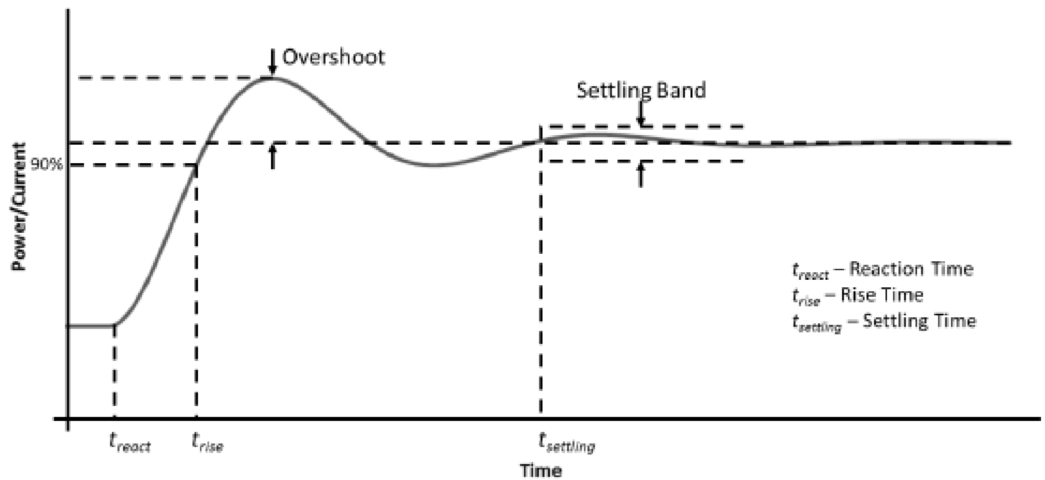


Figure F.1: Power/Current Response Characteristic

NERC Reliability Guideline: BPS-Connected Inverter-Based Resource Performance

Dynamic Performance Requirements for Active and Reactive Power

- Dynamic performance requirement for active power and reactive power (small and large disturbances)
  - Require more robust performance requirements for various system conditions, including normal and weak grid
  - Requirement or ERCOT non biding guideline?
  - Process to review and revise performance requirements due to evolving grid?

Discussions/Next Steps

3.6 Dynamic Model: Challenges and Options for Improvement

- Background:
  - ERCOT/TSPs rely on dynamic models provided by the REs to identify stability constraints and potential mitigation options
  - IBR performance is mainly driven by the controllers and associated settings
  - Increasing user defined models provided and/or suggested by the manufacturers to accurately represent the facility

Challenges and Ongoing Efforts

- ERCOT presented the dynamic model overview/challenges to ROS in March, 2019
  - http://www.ercot.com/content/wcm/key_documents_lists/165178/20._Dynamic_Models_Overview_ROS_Meeting_March_2019.pdf
- ERCOT discussed the potential options for dynamic model improvements in Resource Integration Workshop in March, 2019
  - http://www.ercot.com/content/wcm/key_documents_lists/167477/Dynamic_Model_Follow-up_RI_Workshop_20190321.pptx

Options for Improvement

UDM

- Require UDM to be implemented by the software vendors
- UDM model guideline enforcement

Quality

- Require model performance by REs for model submittal and update for each specific site
- Require benchmark between generic/UDM and PSCAD models/real records for each specific site
- Strengthen model validation requirements

Options for Improvement

Operation Need

- Require the models to be compatible with real time tools (TSAT)

Others

- Require Resource Entities to participate in DWG and to ensure models properly integrate into DWG case
- Eliminate unacceptable models
- Improvement of the existing generic models

Discussions/Next Steps

Ongoing Effort

- Facilitate the model awareness and communication
  - Dynamic model template implementation and RARF model review

Discussions/Suggestions/Next Steps

- Need more discussions on EMT study and PSCAD model

3.7 Measurement and Monitoring

- **Background:**
  - Due to increasing partial trips of IBRs during system events, plant level measurement alone is not sufficient anymore because it is difficult to identify and understand the root causes
  - IBR performance and model validation analysis for these system events would require inverter level measurements (current, voltage, measured frequency and fault codes)
  - Individual inverter measurements are not currently monitored and available to ERCOT

Measurement and Monitoring

- **Inverter data for measurement**
  - Frequency, current and voltage
  - Voltage and current during momentary cessation
  - Voltage and current during reactive current injection
  - Alarm and fault codes
  - DC current and voltage

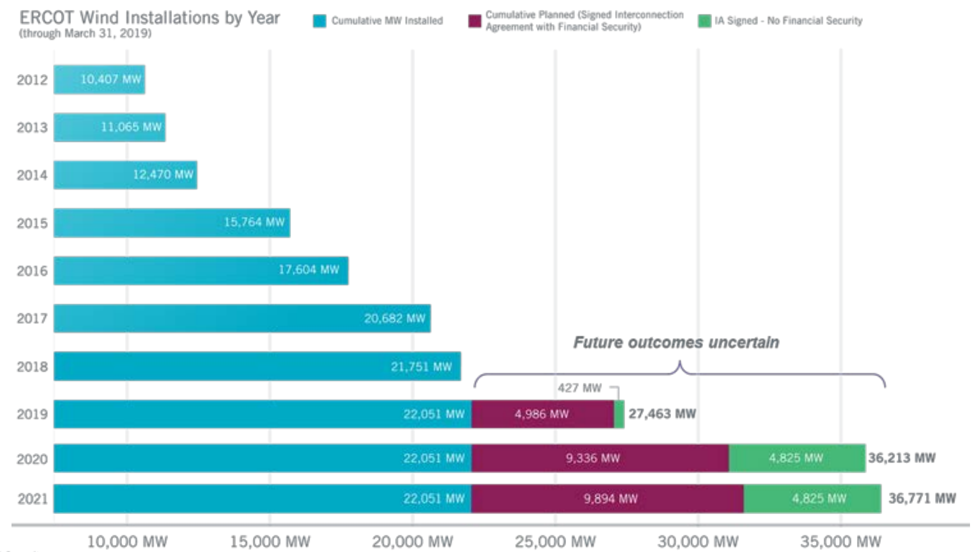
Measurement and Monitoring (continued)

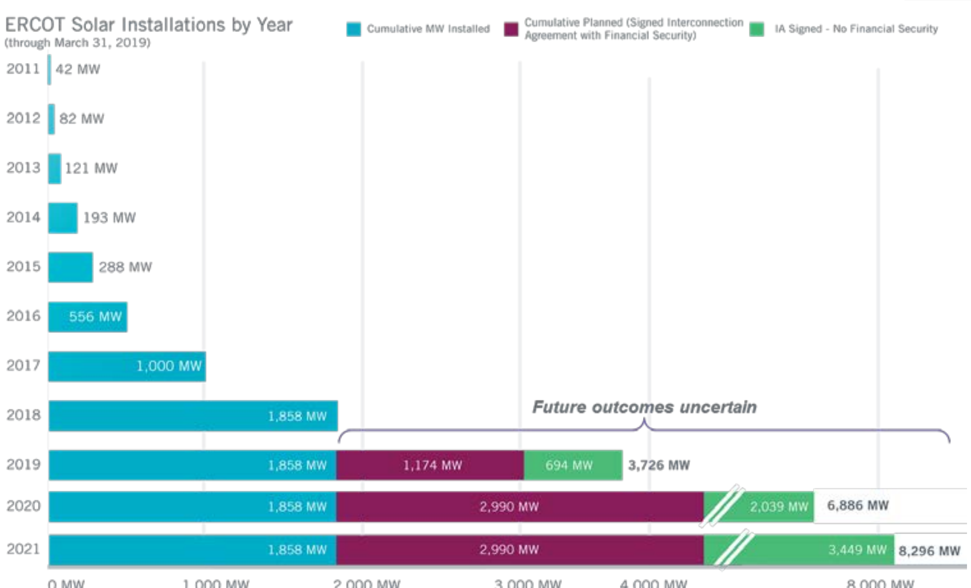
- **Inverter data measurement requirements**
  - Event triggers (Momentary cessation, Voltage or frequency ride through event, others?)
  - Data must be time synchronized
  - Data sampling (in milliseconds?)
  - Event duration – prior to and after the event (in milliseconds of data?)
  - Data storage (for a minimum of 15 or 30 calendar days?)
  - Per inverter, per feeder? Capability available already? Storage concerns/maintenance issues.

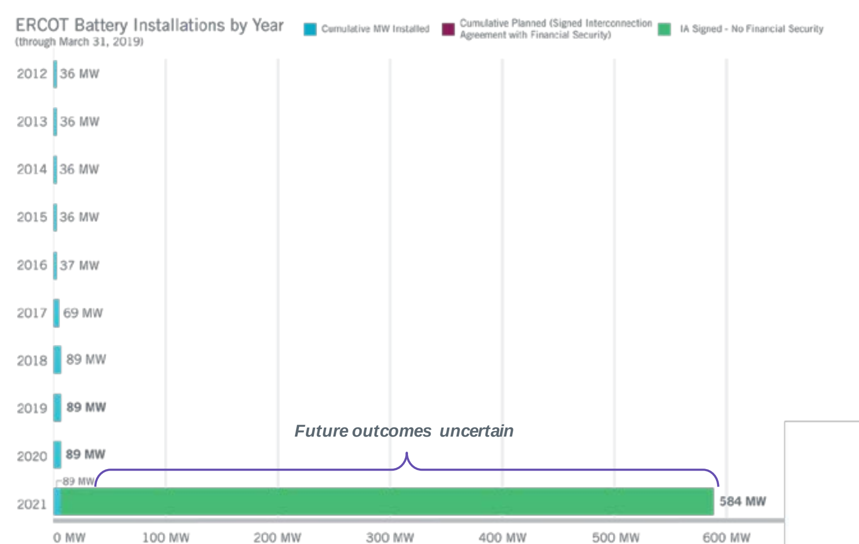
Discussions/Next Steps

3.8 Grid Forming Discussion

- Current Status of Inverter-Based Resources in ERCOT
- All current IBRs in ERCOT are so called Grid Following (GFL) technology





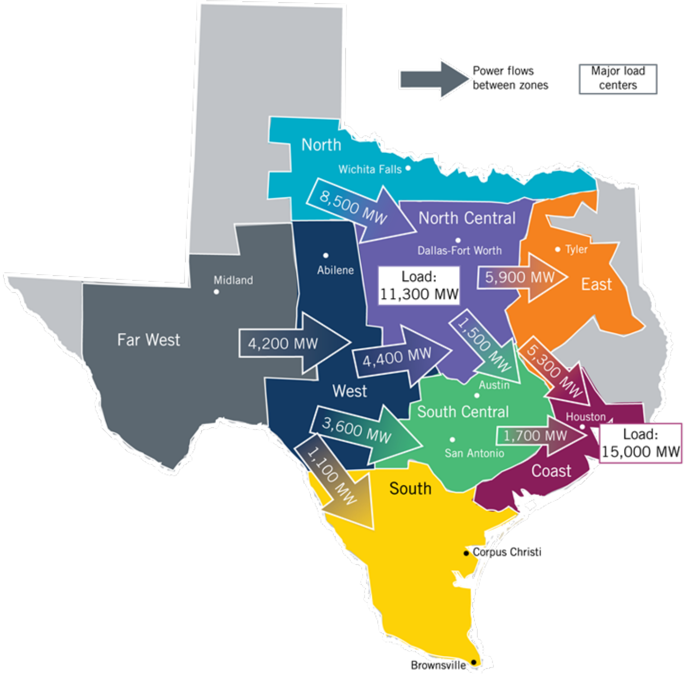


State-of-the-art Grid Following Inverters

- State-of-the-art GFL inverter-based resources (IBR) measure grid variables (voltage, frequency) before starting to react, i.e. behaves like current source.
- GFL IBRs do not contribute to system inertia or system strength
- Inverters have displaced synchronous generators, thereby, exacerbating weak grid and inertia issues.
- GFL IBRs require sufficient system strength to operate and sufficient inertia if providing frequency response.
- Possible operating issues at high GFL IBR penetration:
  - Inverter control interactions
  - Limited current injection could affect the protection and voltage stability
  - Ride through disturbances in low system strength conditions

ERCOT High Penetration Study

- ~70% Penetration of inverter-based wind and solar Resources
- Less synchronous generators
- Reduced system strength
- Significant active and reactive power losses
- IBR controls require sufficient system strength for reliable operation or more robust inverter control capability is required, grid forming
- Synchronous condensers are subject to synchronous machine instabilities (inter & intra area oscillations & angular instability)



Load:	42.2 GW (includes PUNs)
Solar output:	17 GW (90% dispatch)
Wind output:	11 GW (48% dispatch)
West Texas Exports:	15.5 GW (major 345 kV circuits)
Losses (MW):	6%

http://www.ercot.com/content/wcm/lists/144927/Dynamic_Stability_Assessment_of_High_Penertration_of_Renewable_Generatio....pdf

Present Mitigation Measures

- There is a limit of how many GFL IBRs that can be accommodated (due to system strength and inertia issues).

- System operators may limit the output of IBRs and supplement the remaining load with synchronous generators to ensure sufficient inertia and/or sufficient system strength (e.g. Australia, Ireland, Texas).
  - Such operational constraints in the long run may impact further integration of IBRs.

- Alternatively, synchronous condensers are also installed to provide necessary grid support, but may not be a viable long term option.

- Grid forming inverter technology has been considered in recent years.

What is Grid Forming (GFM) Inverter? Still under discussion…

- GFM inverter is capable of supporting the operation of an ac power system under normal, disturbed and emergency conditions without having to rely on services from synchronous generators.
  a) Synthesizes voltage sine-wave with constant frequency without needing external reference
  b) Share load with other generators without explicit communication
  c) Not cause any adverse interactions with other generators and grid devices
  d) Provide black start capability (where needed)
- These capabilities could be subjected to the physical limitations of an inverter, such as short-term current carrying capability and availability of an energy buffer (battery storage, possibly, coupled with a super-capacitor).
- The necessity for, and amount of overcurrent capability beyond the nominal values must be determined based on specific system needs confirmed by studies.
- The capabilities are in addition to the state-of-the-art capabilities of IBRs.

Does GFM Help to Resolve Operating Issues?

- GFM is expected to mitigate some challenges, like weak grid connection.
- Stability challenges not directly caused by the inverter controls, like voltage stability due to long distance large power transfer, may still require other options to be mitigated.

Example: St Eustatius Island

Commercial Pilot deployed in November 2017

- 2.3 MW peak load
- 4.15 MW PV
- 5.9 MWh Li-Ion with grid forming inverters
- 9 diesel gensets

Demonstrated

- Diesel-off mode (100% Storage + Solar)
- Seamless immediate load transfer after generation contingency (simultaneous loss of all gensets at peak load), no load shedding.
- Voltage ride-though for various faults and operating modes.

https://www.smainverted.com/st-eustatius-100-solar-power-in-the-caribbean/

Example: AEMO

- Australian Energy Market Operator (AEMO) enforces minimum inertia requirements in parts of their grid, e.g. South Australia.
- Newly connecting IBRs should also not reduce system strength in the area below pre-determined minimum. TDSPs are conducting screening and full studies (EMT simulations) to assess the impact and propose mitigation measures. Interconnecting Entity is responsible for the cost of implementation of these measures.
- The measures may include:
  - Network upgrades,
  - Synchronous condensers,
  - Contracting synchronous generation for provision of system strength,
  - **Use of GFM technology** allowing the resource to stably operate down to 0 short circuit ratio,
  - Controller tuning of the existing IBRs
  - Remedial Action Schemes (post-contingency)

OEM Challenges

- Large scale GFM for bulk power system application are not commercially available (this does not mean it is not doable!)
- OEMs need clear performance requirements to design products; development efforts and additional cost of modifying inverters are highly dependent on it.
- Grid forming technology is not only about inverter control algorithms:
  - PV and Wind Turbine design/control based on maximum energy capture, while GFM operation could significantly depart from that;
  - Consideration needs to be given to energy buffer and transient overcurrent capability of the inverter;
- Trade-off between investments in R&D of new features and market volume for the GFM inverters.

Circular problem

Comparison of Technology Capabilities

IBR capabilities below limited by inverter overcurrent capability (for both GFM and GFL) and size of energy buffer (for GFM)

	Synch Gen	Synch Cond	GFL IBR	GFM IBR
Contribution to system strength	Yes	Yes	No	Yes(1)
Fault Current Contribution	Yes	Yes	Limited	Yes(1)
Susceptible to lack of system strength	No	No	Yes	No
Primary Frequency Response	Yes	No	Yes	Yes
Fast Frequency Response (2)	No	No	Yes	Yes
Inertia Contribution	Yes	Yes	No	No
Provides Energy	Yes	No	Yes	Yes

(1). GFM is expected to require larger inverter size that can contribute high fault current
(2). Respond within 0.5 second or faster

Based on: AEMO, Synchronous condensers and inverters, presentation by B. Badrzadeh and S. Grogan, 2018

Discussions/Next Steps

- Developing functional specifications/requirements without being overly prescriptive; let any capable technology to come and provide.
- Allow developers with GFM capability gain access to network locations where operation constraints otherwise would be imposed.
- Interconnection requirement for all new IBRs to be grid forming (effective e.g. in 3~5 years)

4. Workshop Summary and Next Steps

- Summary
- Next Steps
- Other topics that may also require discussions but are not covered in this workshop
  - Protection, fault current contribution
  - PSCAD models and study requirements
  - Others?