NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Inverter-Based Resource Disturbance Analysis

Key Findings and Recommendations

Informational Webinar
February 15, 2018

RELIABILITY | ACCOUNTABILITY




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NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

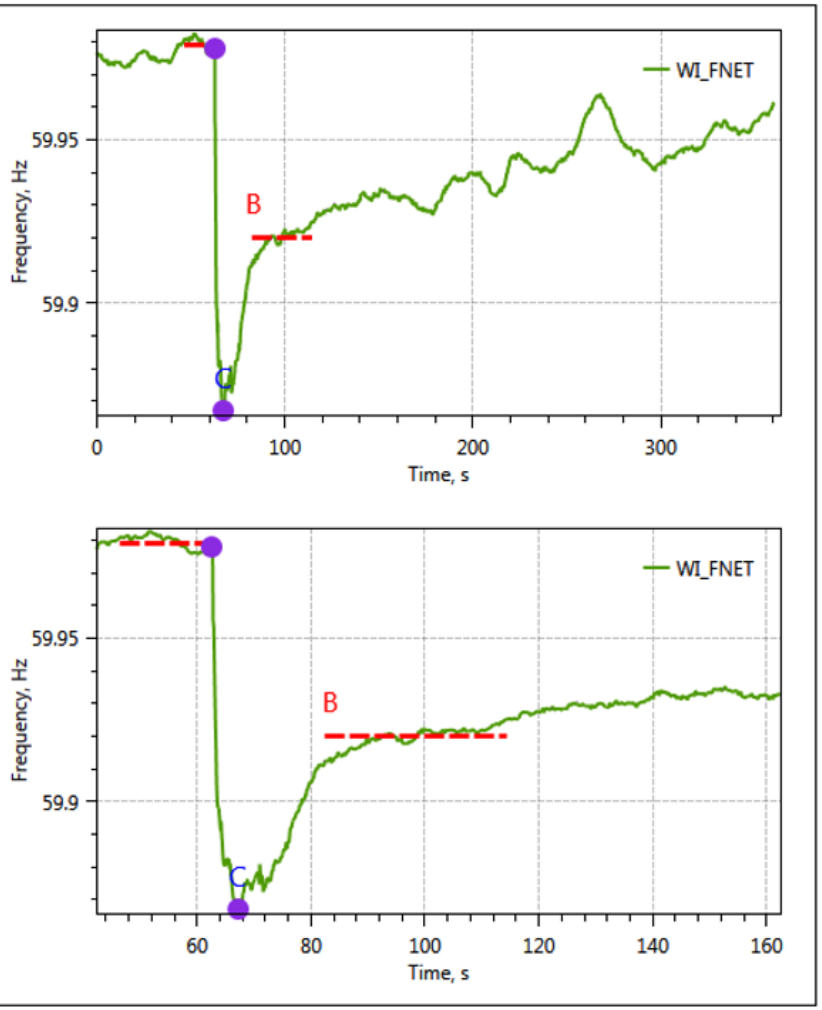
August 16, 2016
Blue Cut Fire Disturbance

Key Findings and Recommendations

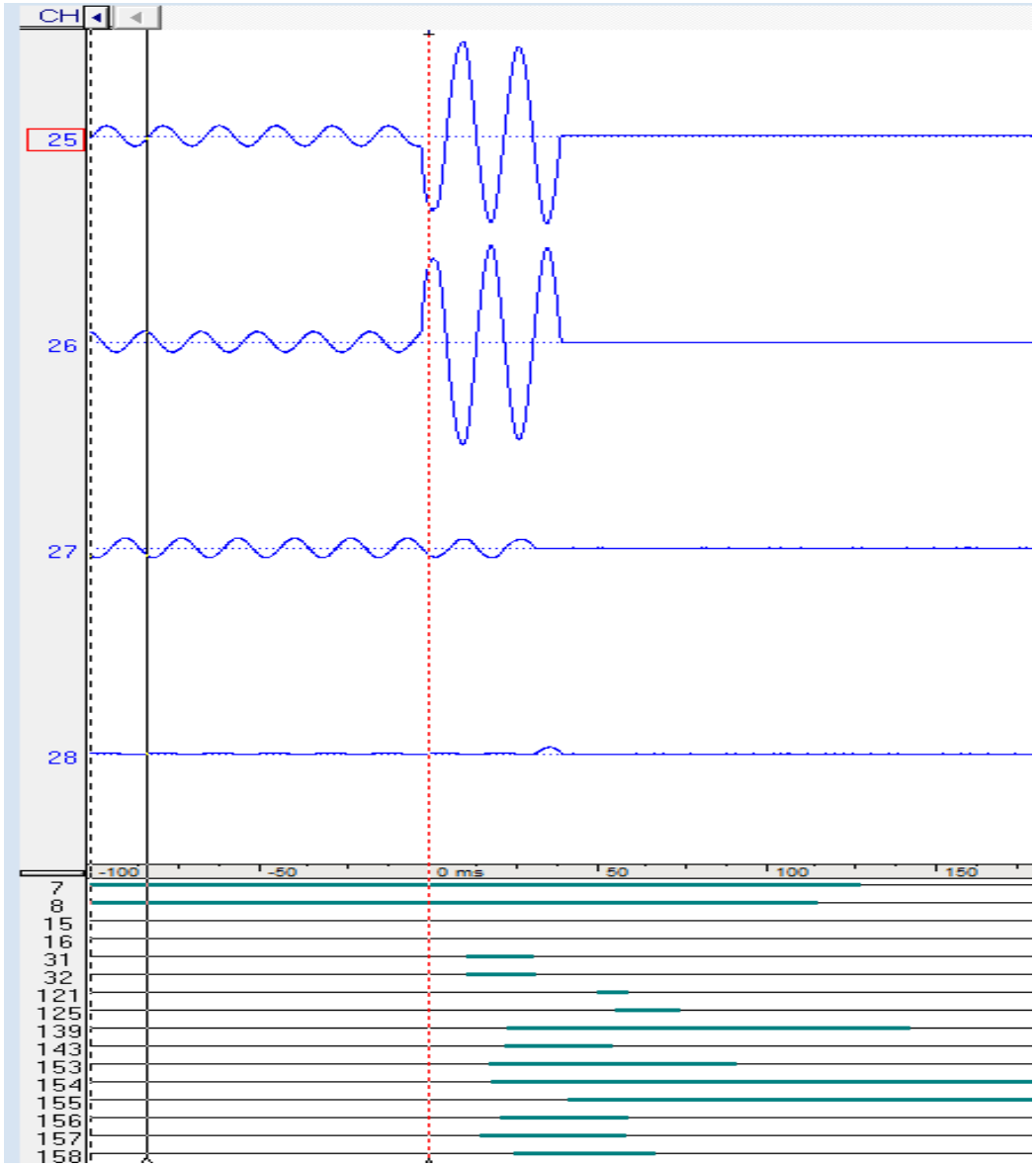
Western Interconnection Frequency

WI_20160816_184506

Event ID	WI_20160816_184506
Event Description	""
UTC Time	08/16/2016 18:45:06
Local Time	08/16/2016 11:45:06
Time Zone	PDT
M4 Flag	Yes
BAL003 Flag	Yes
MW Loss	0
Value A	59.979
Value B	59.92
Point C	59.8669
Time of C	4.7
Point C'	-
Time of C'	-
A-B [mHz]	59
A-C [mHz]	112
FRM_B [MW/0.1Hz]	0
FRM_C [MW/0.1Hz]	0



500 kV Fault Trace



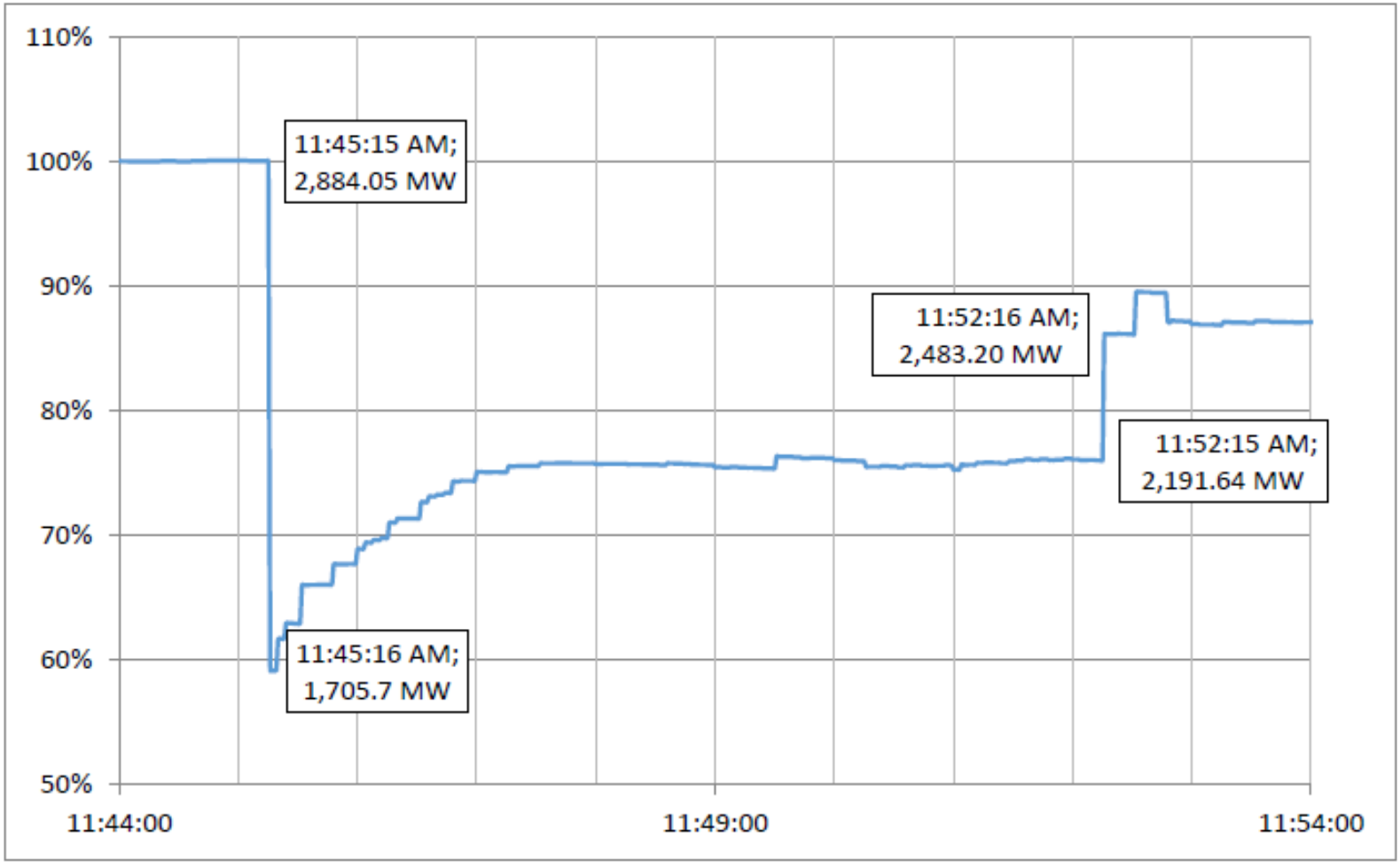
Phase A amps

Phase B amps

Phase C amps

Residual amps

Solar Resource Loss



Data Gathering

- 26 different solar developments
- All utility scale
- Majority connected at 500kV or 230kV
- 10 different inverter manufacturers
- Reported causes of “trips”
  - Under frequency
  - Under voltage
  - Over voltage
  - DC overcurrent
  - 1 loss of synchronism

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Not an Isolated Event

#	Date/Time	Fault Location	Fault Type	Clearing Time (cycles)	Lost Generation (MW)	Geographic Impact
1	08/16/2016 11:45	500 kV line	Line to Line (AB)	2.49	1,178	Widespread
2	08/16/2016 14:04	500 kV line	Line to Ground (AG)	2.93	234	Somewhat Localized
3	08/16/2016 15:13	500 kV line	Line to Ground (AG)	3.45	311	Widespread
4	08/16/2016 15:19	500 kV line	Line to Ground (AG)	3.05	30	Localized
5	09/06/2016 13:17	220 kV line	Line to Ground (AG)	2.5	490	Localized
6	09/12/2016 17:40	500 kV line	Line to Ground (BG)	3.04	62	Localized
7	11/12/2016 10:00	500 kV CB	Line to Ground (CG)	2.05	231	Widespread
8	02/06/2017 12:13	500 kV line	Line to Ground (BG)	2.97	319	Widespread
9	02/06/2017 12:31	500 kV line	Line to Ground (BG)	3.01	38	Localized
10	02/06/2017 13:03	500 kV line	Line to Ground (BG)	3.00	543	Widespread
11	05/10/2017 10:13	500 kV line	unknown	unknown	579	Somewhat Localized

Key Finding #1

- Largest block of solar PV loss (~700 MW) due to underfrequency tripping
- Inverter sensed a near instantaneous frequency of <57 Hz and tripped instantaneously

What Was the Frequency?

WI_20160816_184506

Event ID	WI_20160816_184506
Event Description	""
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A-C [mHz]	112
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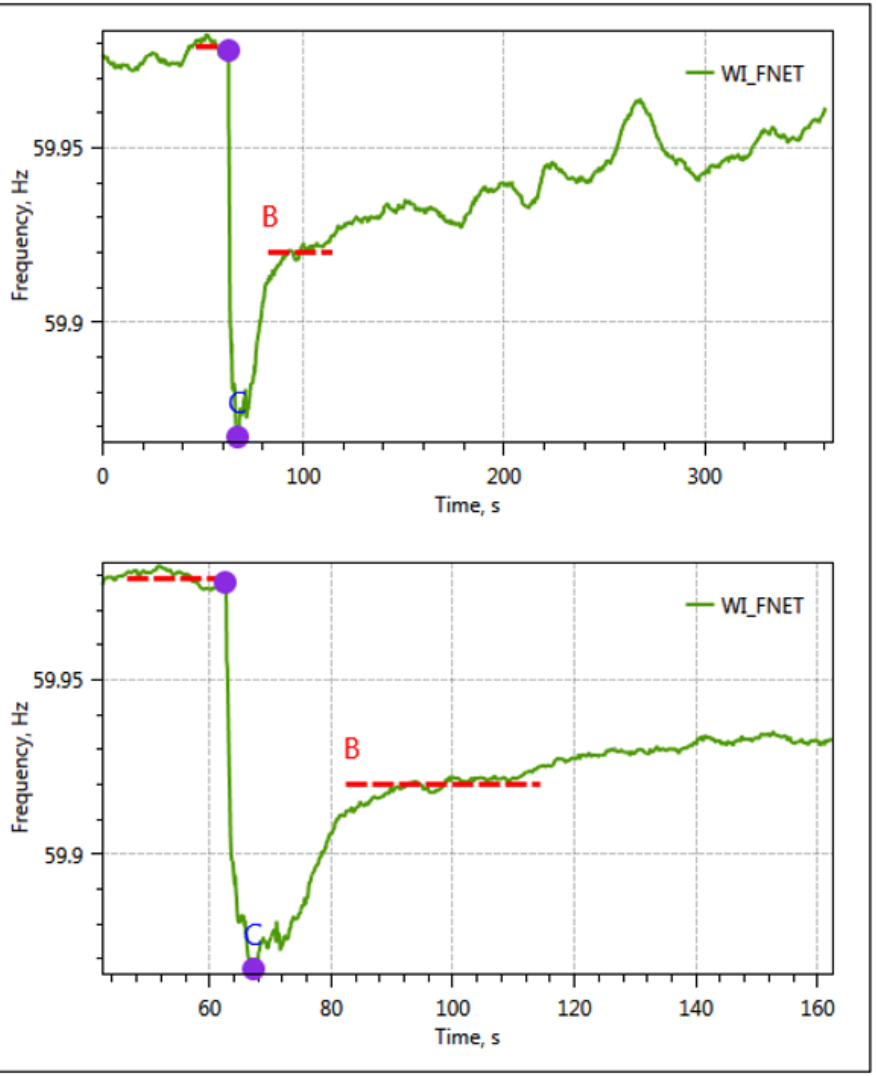
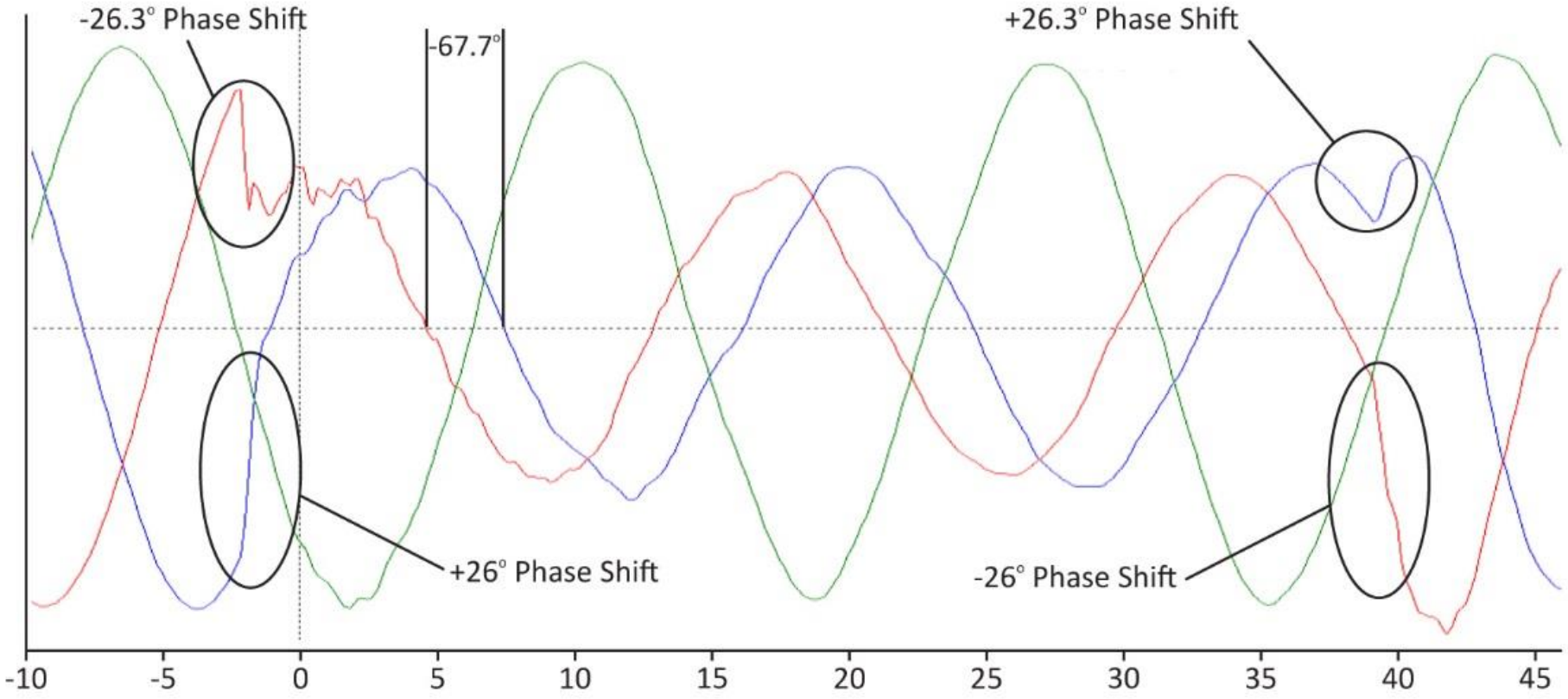
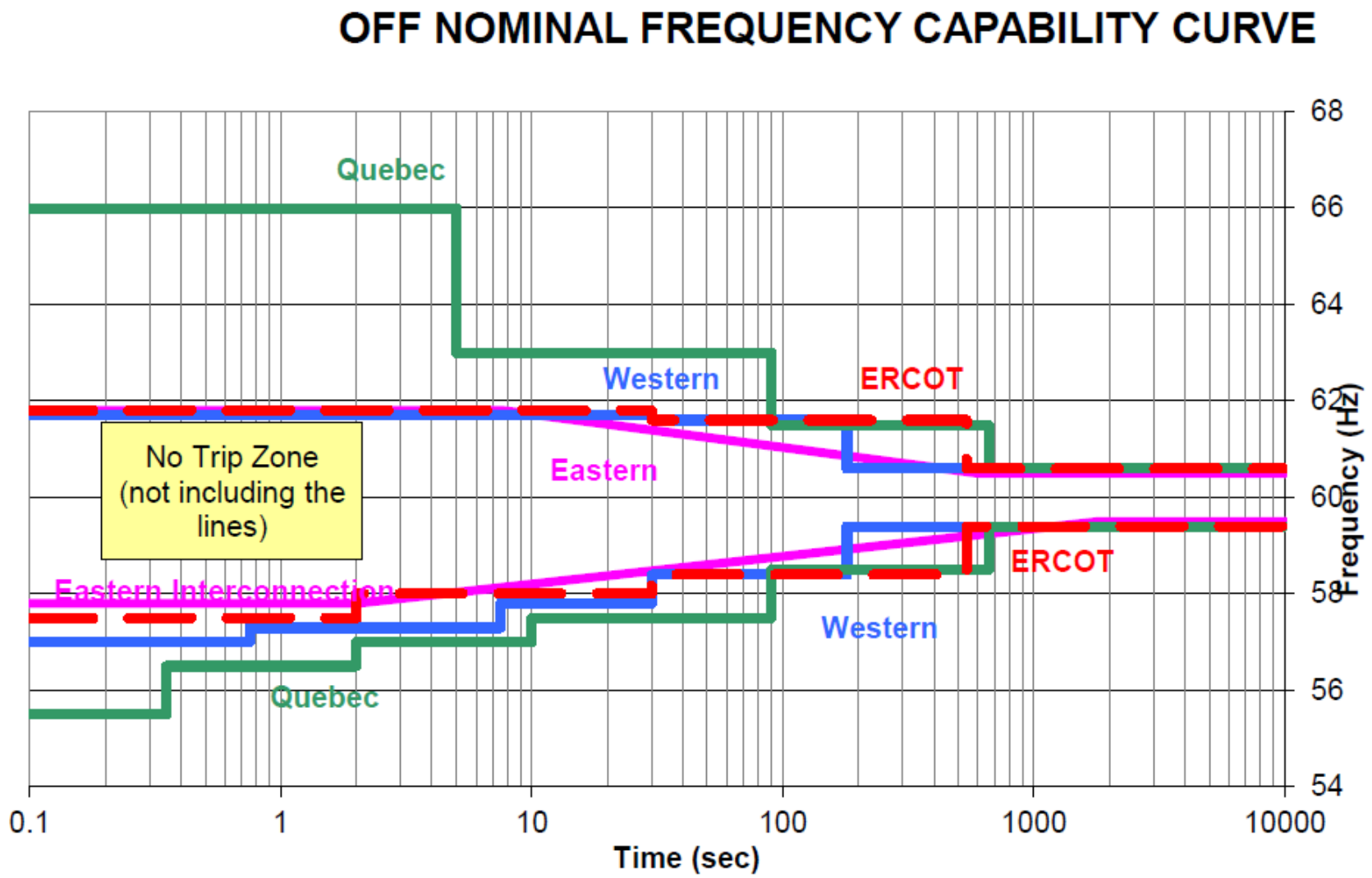


"Phase Jump"


-26.3° Phase Shift
-67.7°
+26.3° Phase Shift
+26° Phase Shift
-26° Phase Shift
-10
-5
0
5
10
15
20
25
30
35
40
45

PRC-024-2 Frequency Ride-Through Curve



Issues

Curve Data Points:

Eastern Interconnection

High Frequency Duration		Low Frequency Duration	
Frequency (Hz)	Time (Sec)	Frequency (Hz)	Time (sec)
≥61.8	Instantaneous trip	≤57.8	Instantaneous trip
≥60.5	$10^{(90.935-1.45713*f)}$	≤59.5	$10^{(1.7373*f-100.116)}$
<60.5	Continuous operation	> 59.5	Continuous operation

Western Interconnection

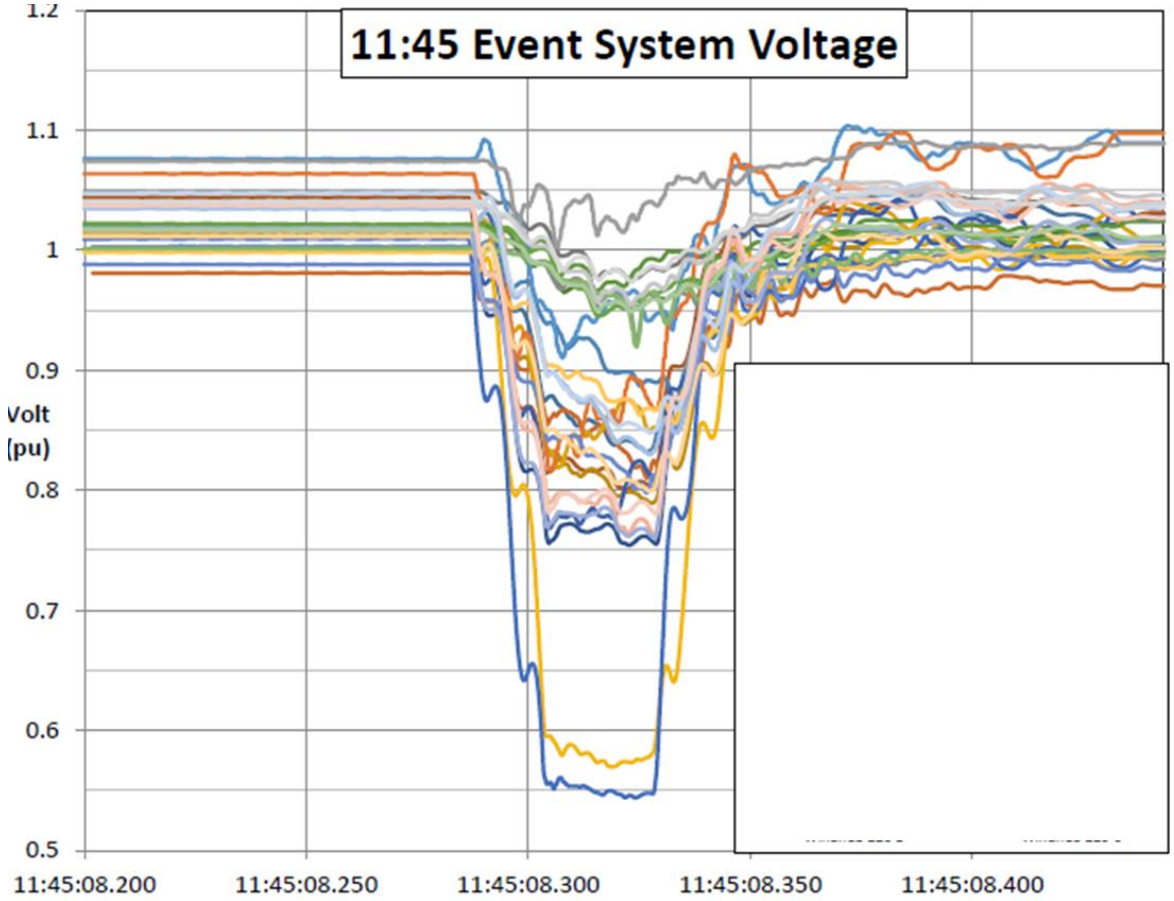
High Frequency Duration		Low Frequency Duration	
Frequency (Hz)	Time (Sec)	Frequency (Hz)	Time (sec)
≥61.7	Instantaneous trip	≤57.0	Instantaneous trip
≥61.6	30	≤57.3	0.75
≥60.6	180	≤57.8	7.5
<60.6	Continuous operation	≤58.4	30
		≤59.4	180
		>59.4	Continuous operation

Key Finding #1

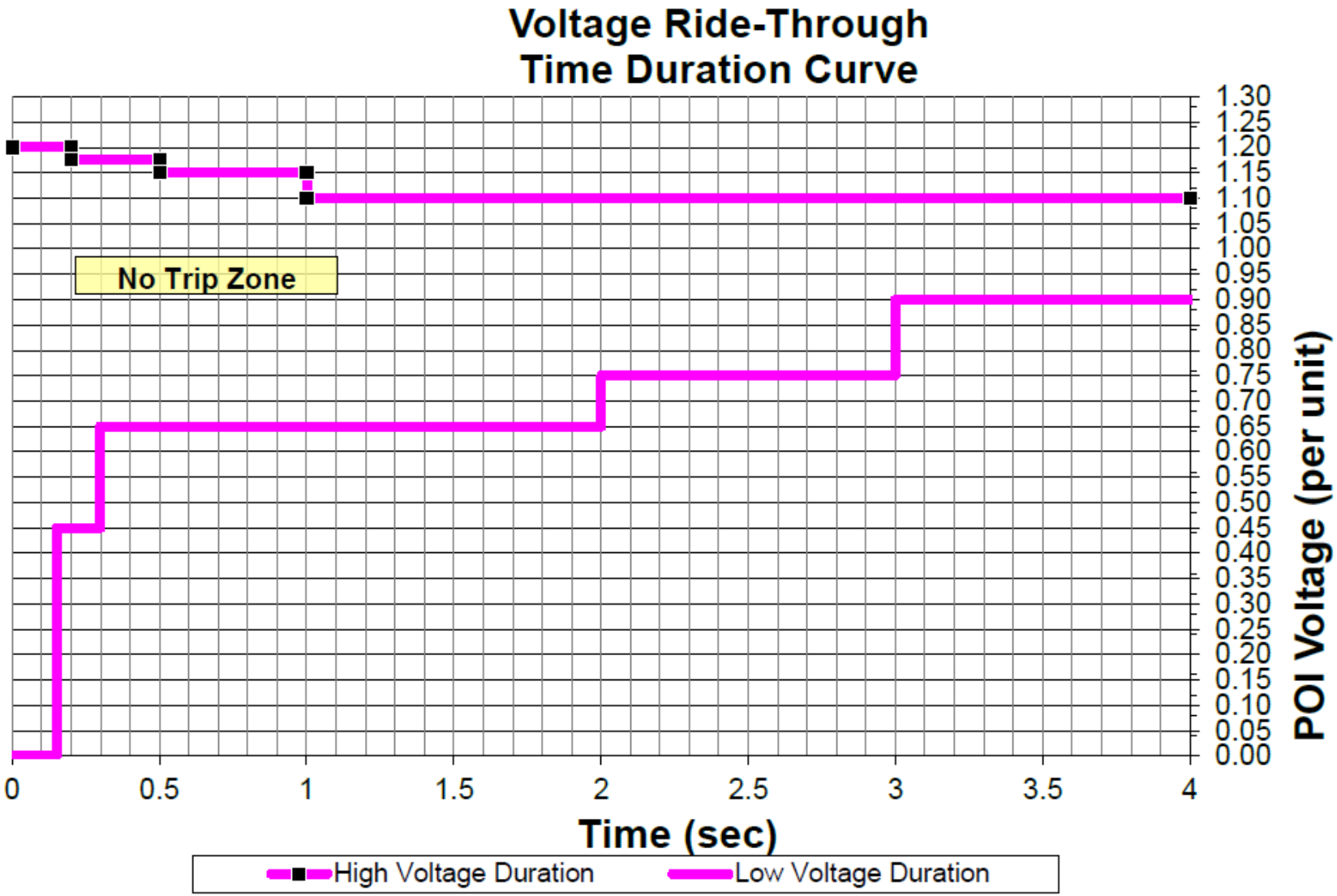
- Isolated to one inverter manufacturer
- Manufacturer quickly devised solution following event
- Added time delay to inverter frequency tripping
  - Allows inverter to “ride through” transient/distorted waveform period without tripping.

Key Finding #2: Undervoltage Tripping

- 2nd largest block of inverter loss (~450 MW) was attributed to low voltage



PRC-024-2 Voltage Ride-Through Curve

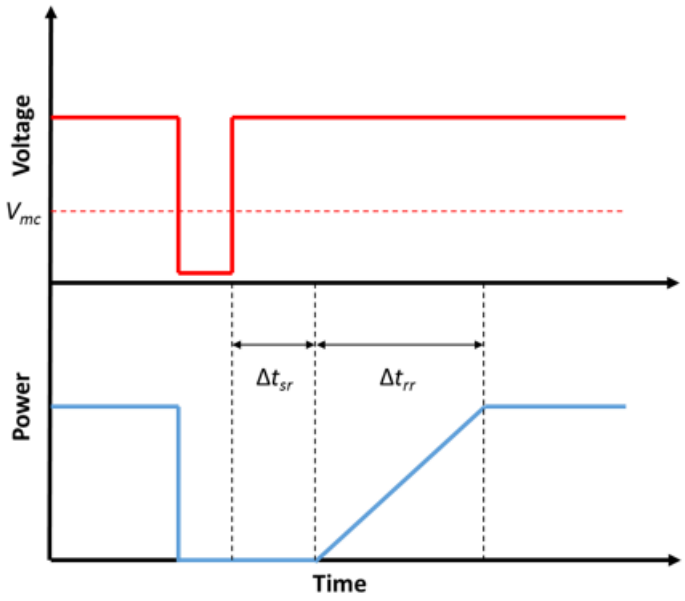


Key Finding #2

- Inverters have three modes of operation
  - Operating (injecting active current into the system)
  - Momentary Cessation (momentarily cease to inject current during voltages outside continuous operating range - .9 to 1.0 per unit)
  - Trip (cease to inject current, disconnect from grid, wait ~ five minutes and return to service if grid voltage and frequency are within bounds)

Key Finding #2

- The inverters did not “Trip”, they went into Momentary Cessation
- Majority of installed inverters set to momentarily cease current injection for voltages of V < .9 p.u. or V > 1.1 p.u.
- In inverter language, Momentary Cessation does not equal trip



Actions in response to Blue Cut Fire

- Frequency tripping
  - Manufacturer is adding tripping delay
- Simulations to identify momentary cessation risk
  - ~7200 MW potential
  - Specify maximum delay and ramp rate for Restore Output

Key Findings and Recommendations

- NERC Alert/Recommendation to Industry was issued 6/20/2017
  - Work with inverter manufacturer to ensure no erroneous frequency tripping
  - If momentary cessation is used, restore output in no more than 5 seconds

Alert responses

Susceptible to Erroneous Frequency Calculations?			
	MW	Responses	Inverter units
Yes	6,244	74	7,148
No	10,527	76	7,230
Total	**16,771**	**150**	**14,378**

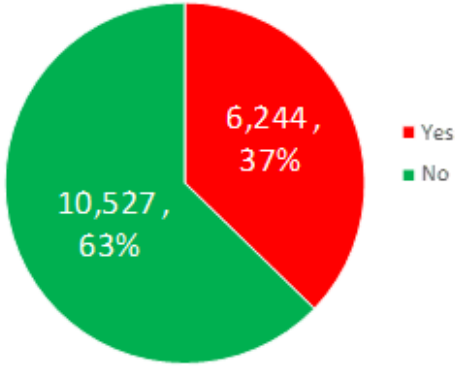


Figure 2: MW susceptible to Erroneous Frequency Calculations

Alert responses

Inverter cease output during abnormal voltages?			
	MW	Responses	Inverter units
Yes	14,113	119	11,821
No	2,657	31	2,557
Total	**16,771**	**150**	**14,378**

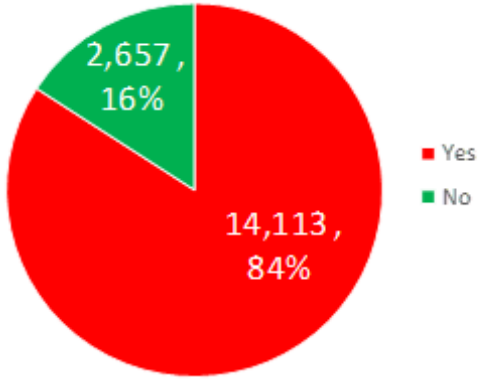


Figure 4: MW cease output during abnormal voltages

Key Findings and Recommendations

- Further study needed for risk associated with momentary cessation (IRPTF)
- Clarify that outside the PRC-024 frequency and voltage ride-through curves are may trip, not must trip
- Review PRC-024 to determine if any changes are needed

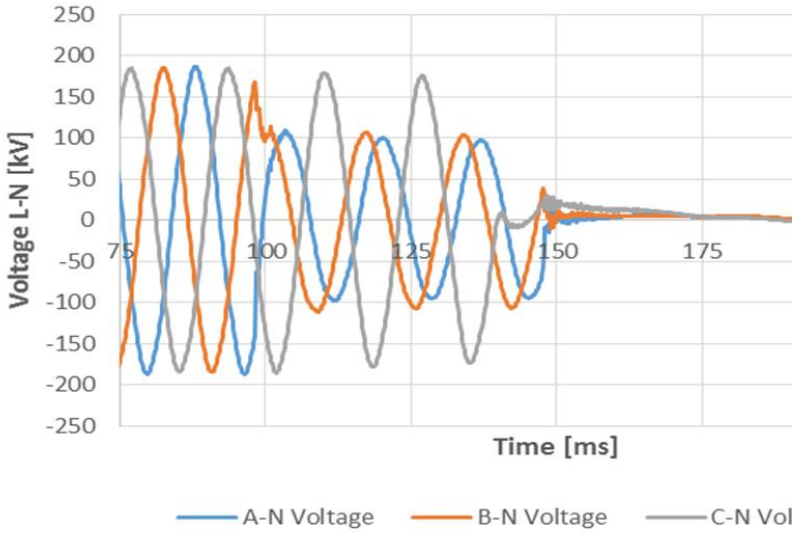
October 9, 2017
Canyon 2 Fire Disturbance

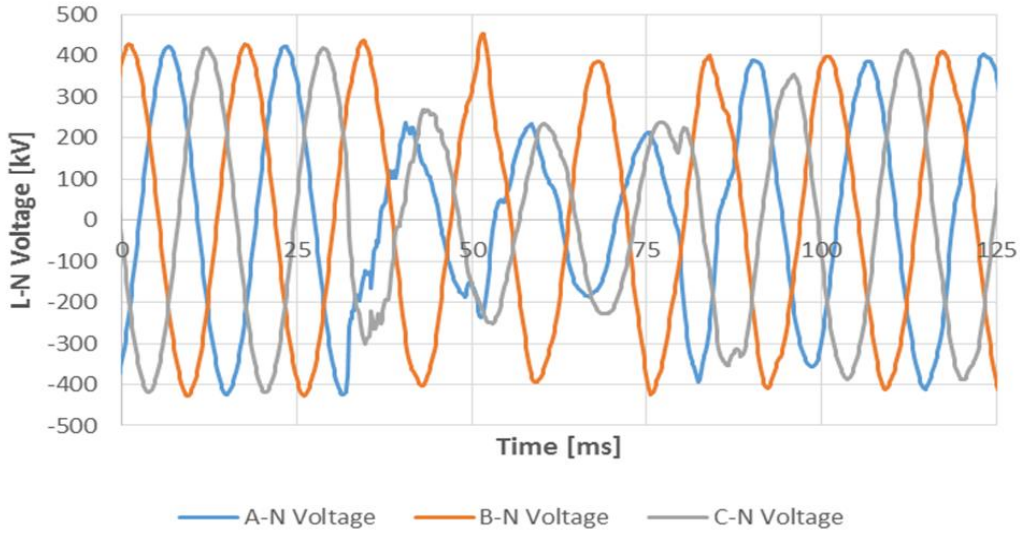
Key Findings and Recommendations

Map of Affected Area

Two Fault Events

Smoke-induced L-L fault events caused by Canyon 2 Fire…
Both fault cleared normally…

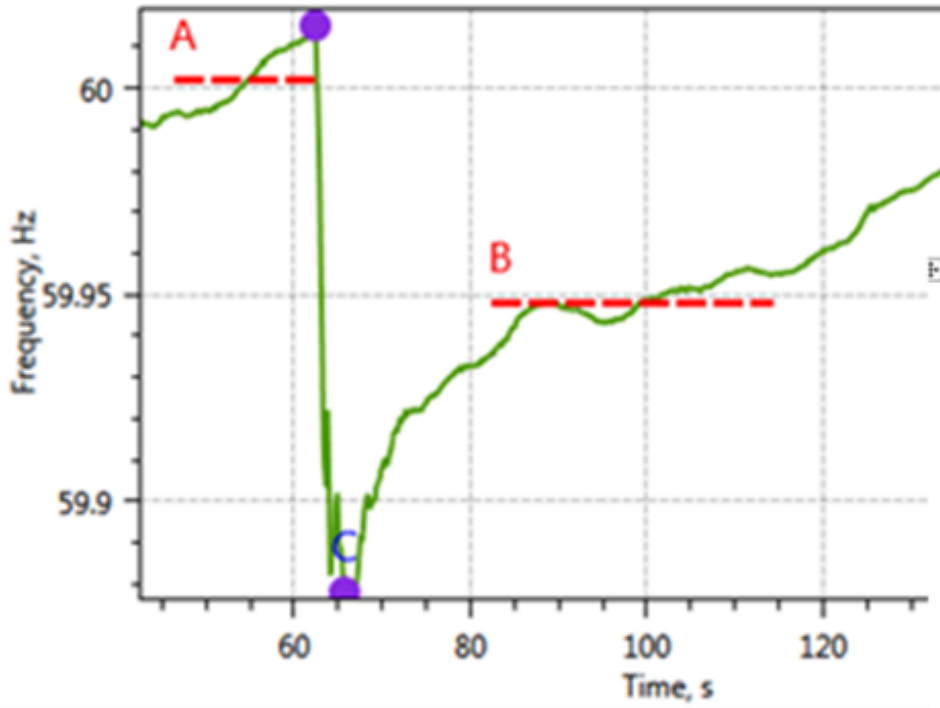




<u>Fault Event 1:</u>
220 kV
L-L Fault
< 3 cycle clearing

<u>Fault Event 2:</u>
500 kV
L-L Fault
< 3 cycle clearing

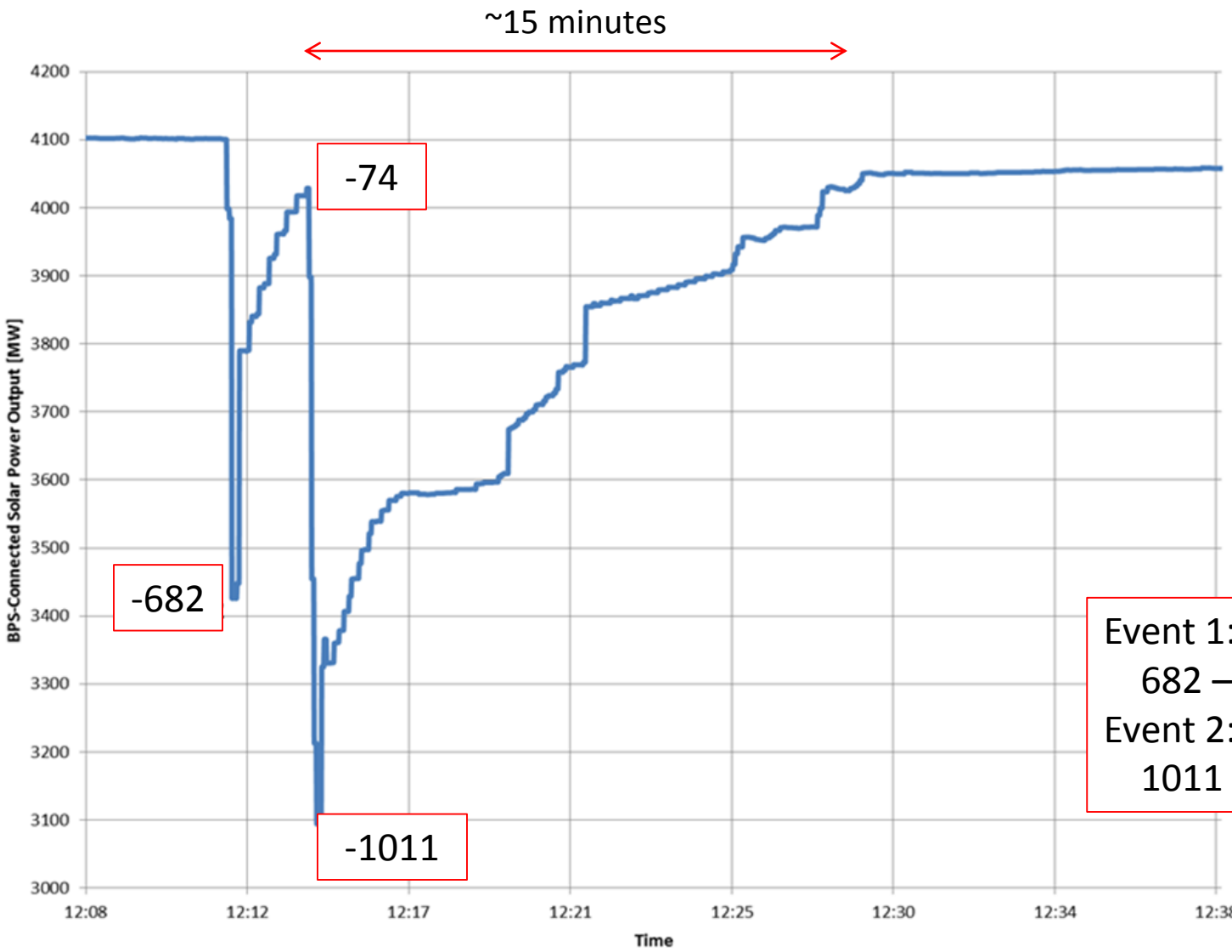
Frequency Response from 500 kV Fault Event #2



WI_20171009_191428

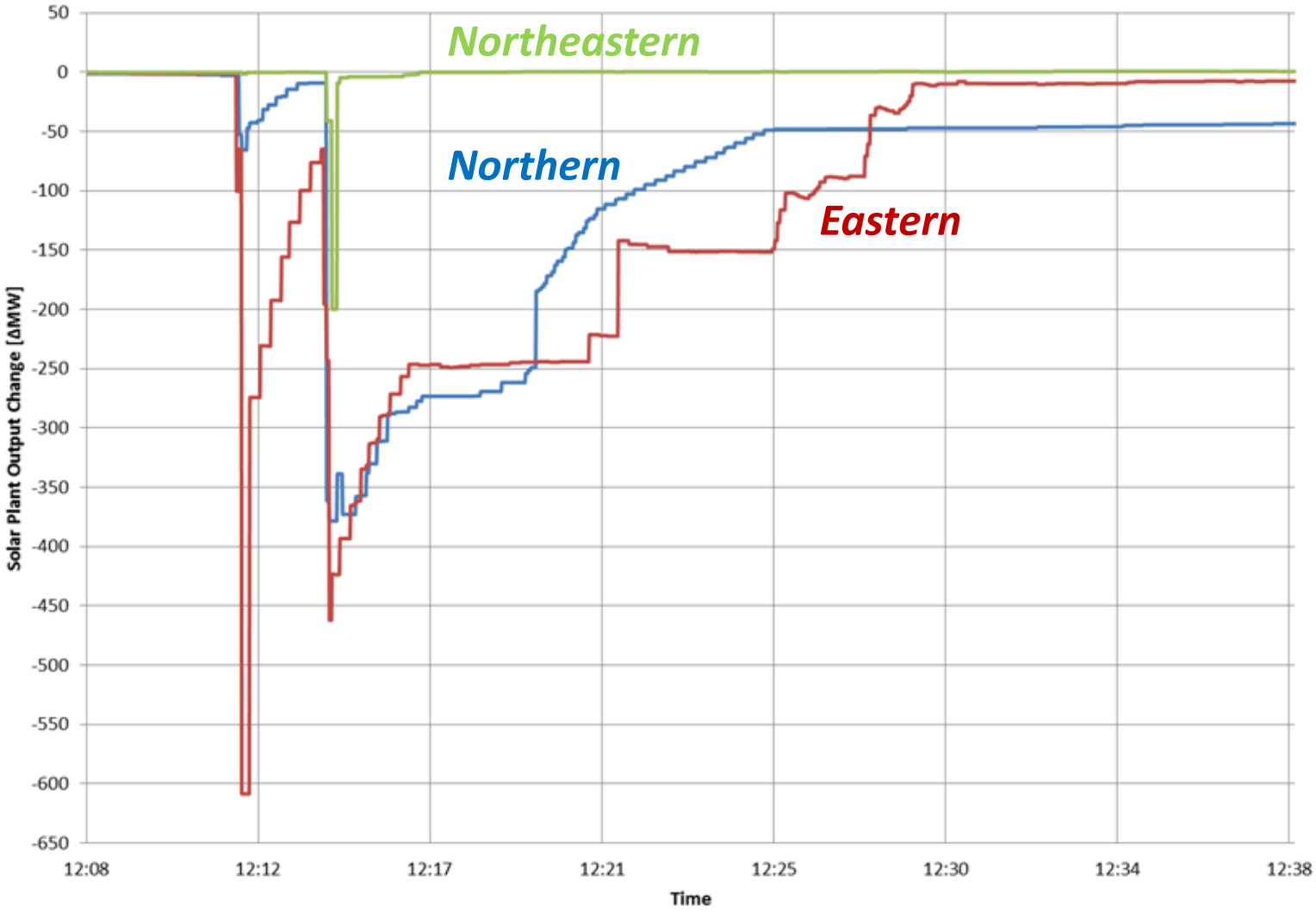
Event ID	WI_20171009_191428
Event Description	"Solar Generation 900MW loss"
UTC Time	10/09/2017 19:14:28
Local Time	10/09/2017 12:14:28
Time Zone	PDT
M4 Flag	Yes
BAL003 Flag	Yes
MW Loss	900
Value A	60.002
Value B	59.948
Point C	59.878
Time of C	3.3
Point C'	-
Time of C'	-
A-B [mHz]	54
A-C [mHz]	124
FRM_B [MW/0.1Hz]	1667
FRM_C [MW/0.1Hz]	726

Aggregate SCE Solar PV Performance SCADA Data

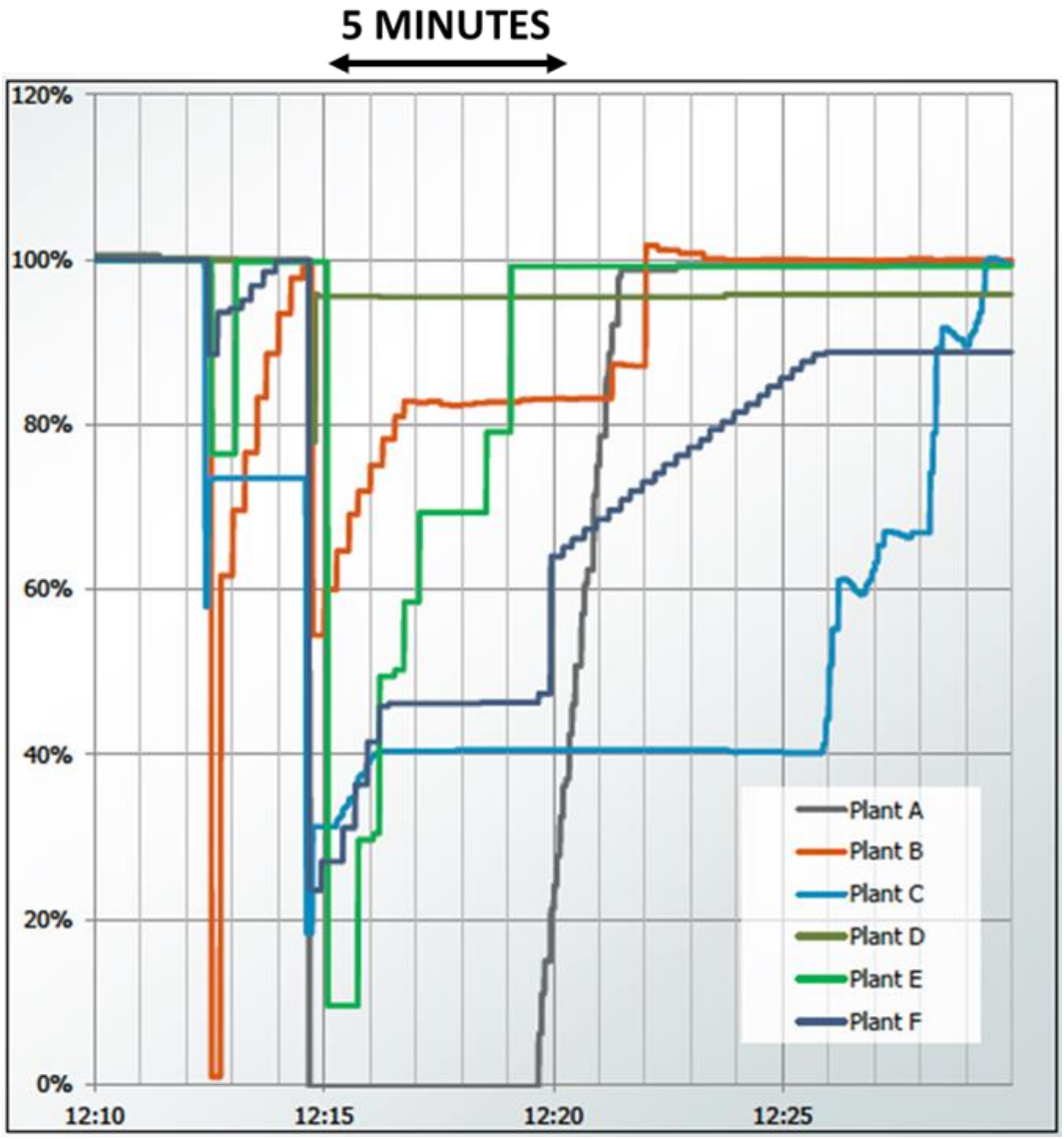


Event 1:
682 – 0 = 682 MW
Event 2:
1011 – 74 = 937 MW

Solar PV Outputs



Solar PV Outputs



Key Findings

1. No erroneous frequency tripping
2. Continued use of momentary cessation
3. Ramp rate interactions with return from momentary cessation
4. Interpretation of PRC-024-2 voltage ride-through curve
5. Instantaneous voltage tripping and measurement filtering
6. Phase lock loop synchronization issues
7. DC reverse current tripping
8. Transient interactions and ride-through considerations

Key Findings #1

No erroneous frequency tripping

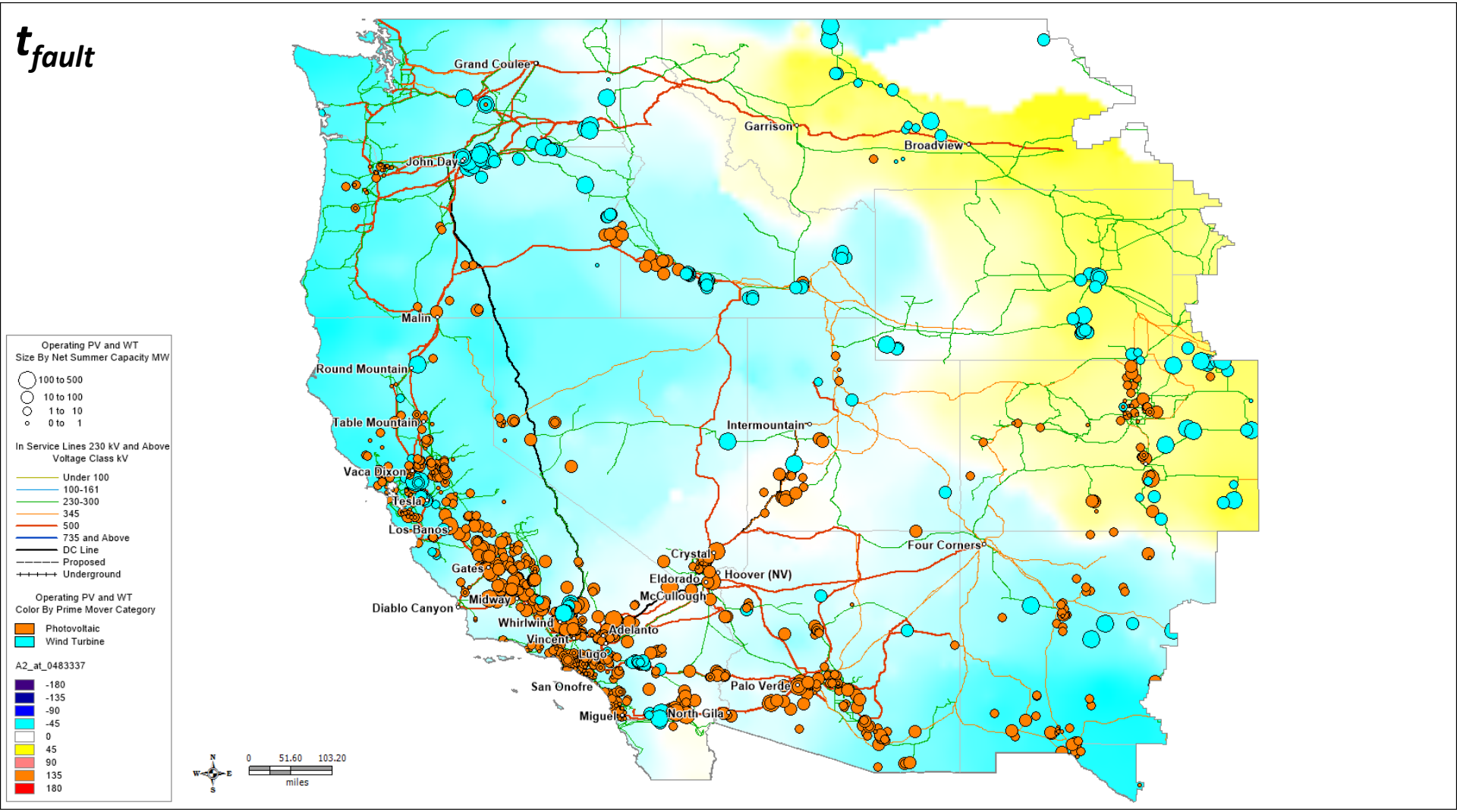
- Alert recommended GOPs and GOs ensure inverter controls do not erroneously trip on instantaneous frequency measurements
- By October 9, 2017 event, 97% of inverter manufacturer's BPS-connected fleet had been updated
- Mitigating actions by inverter manufacturer and GOs appear to have worked

Key Findings #2

Continued use of momentary cessation

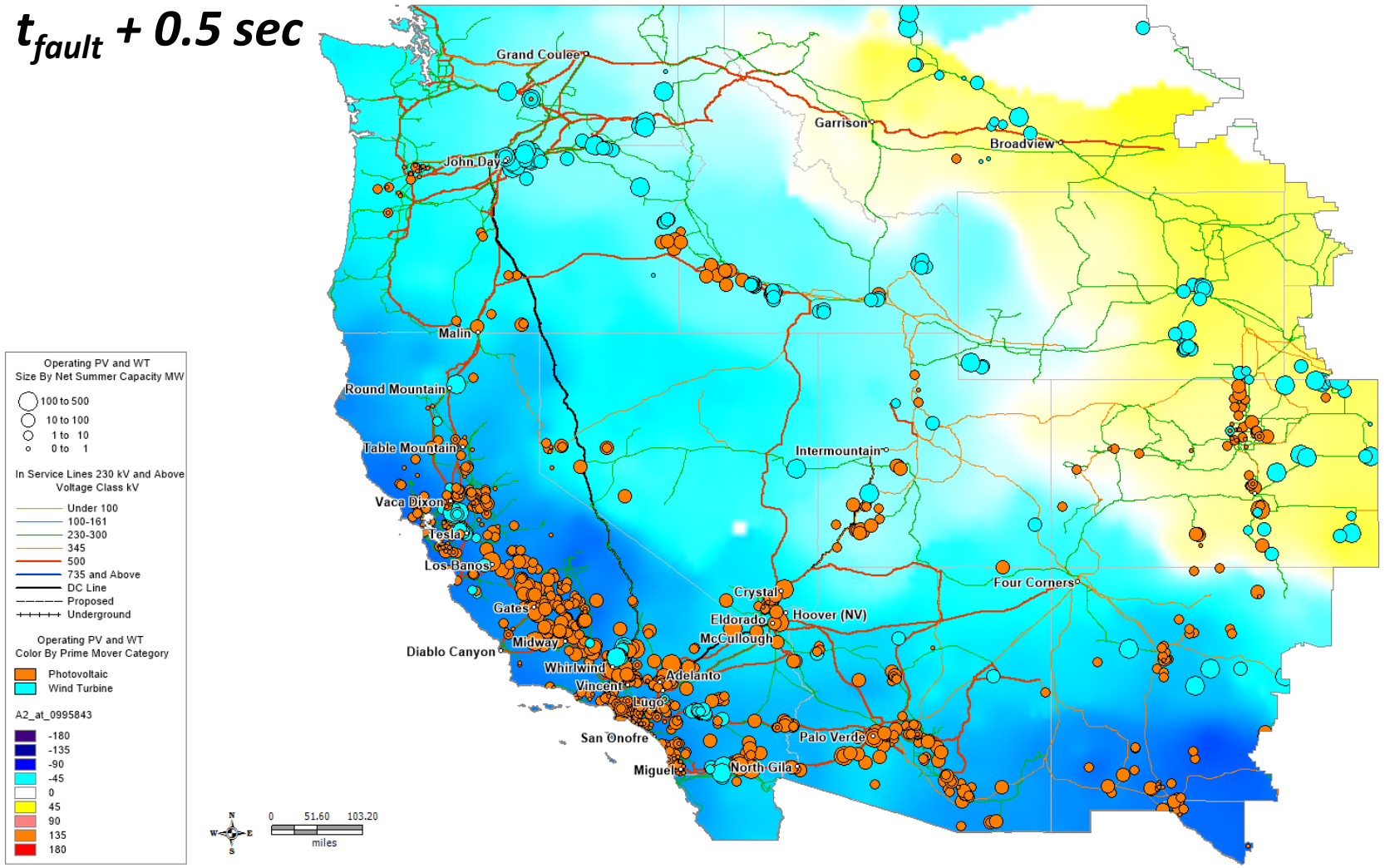
- Majority of existing inverters use momentary cessation
- Most use a low voltage threshold of ~0.9 pu
- Recovery of current following momentary cessation varies, relatively slow for grid dynamics
- Blue Cut Fire recommendation – interim solution
- NERC IRPTF studies – new recommendation
  - Stability studies show potential BPS wide-area stability issues

Clarification and Recommendation for Momentary Cessation

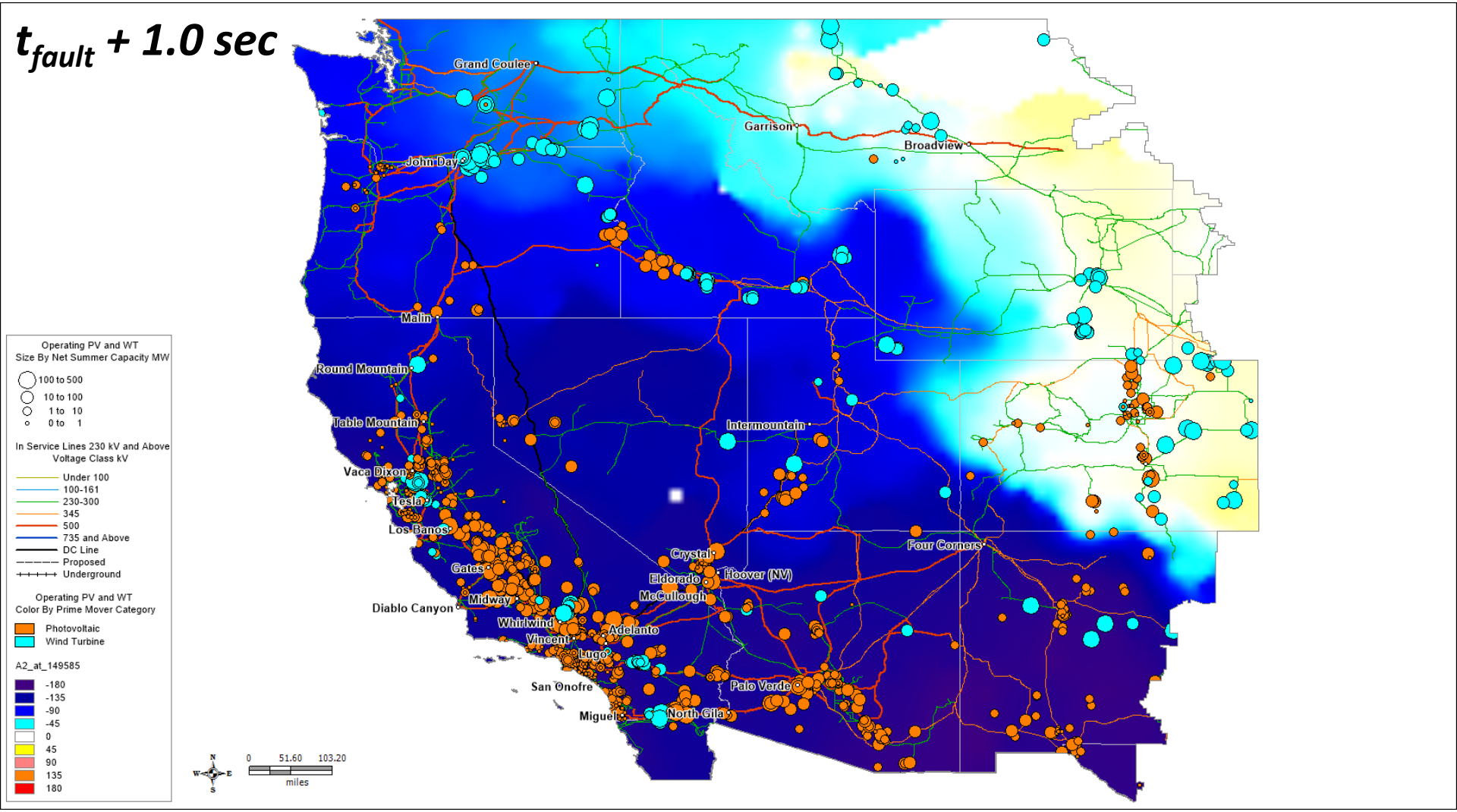


Clarification and Recommendation for Momentary Cessation

t_{fault} + 0.5 sec

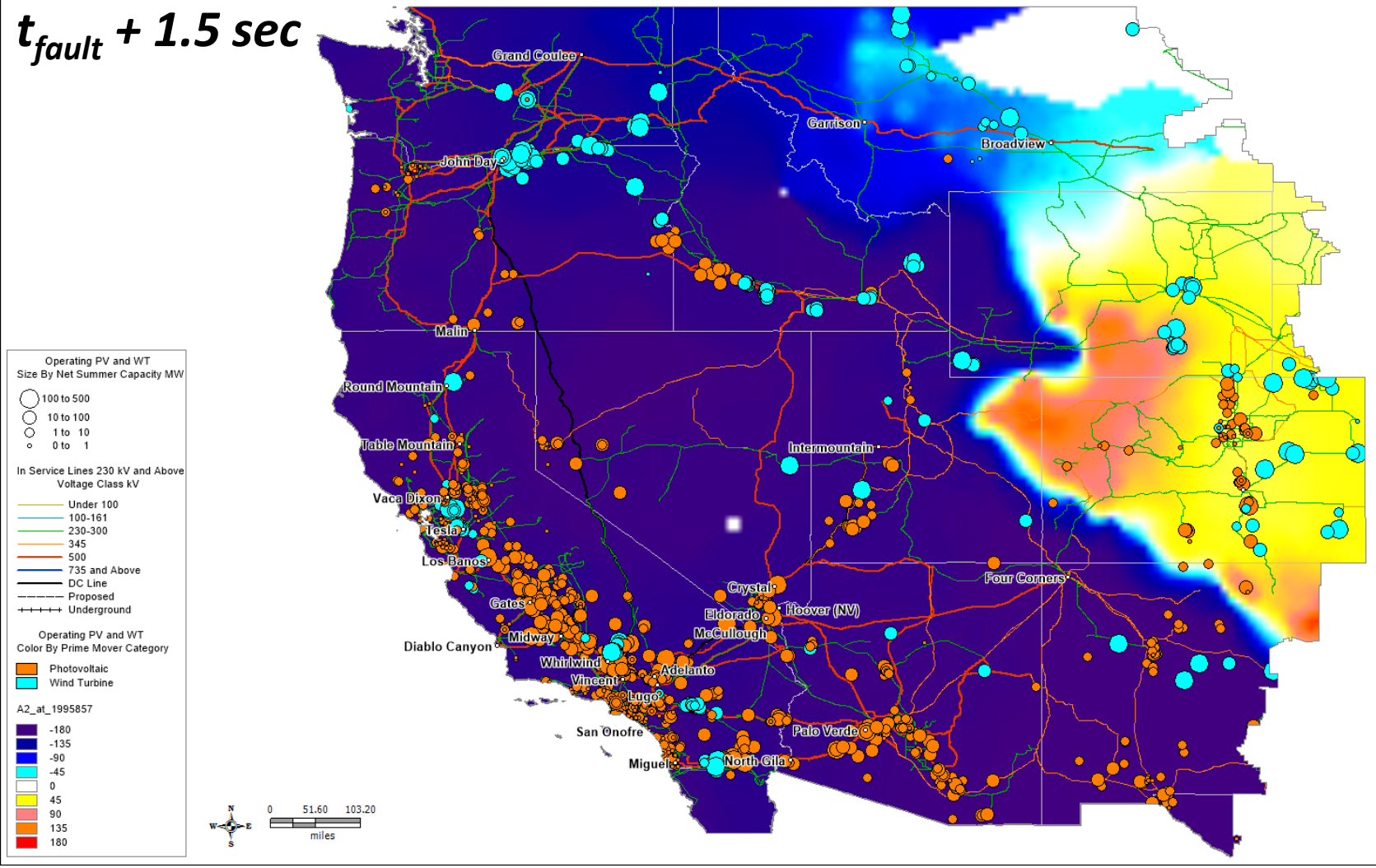


Clarification and Recommendation for Momentary Cessation

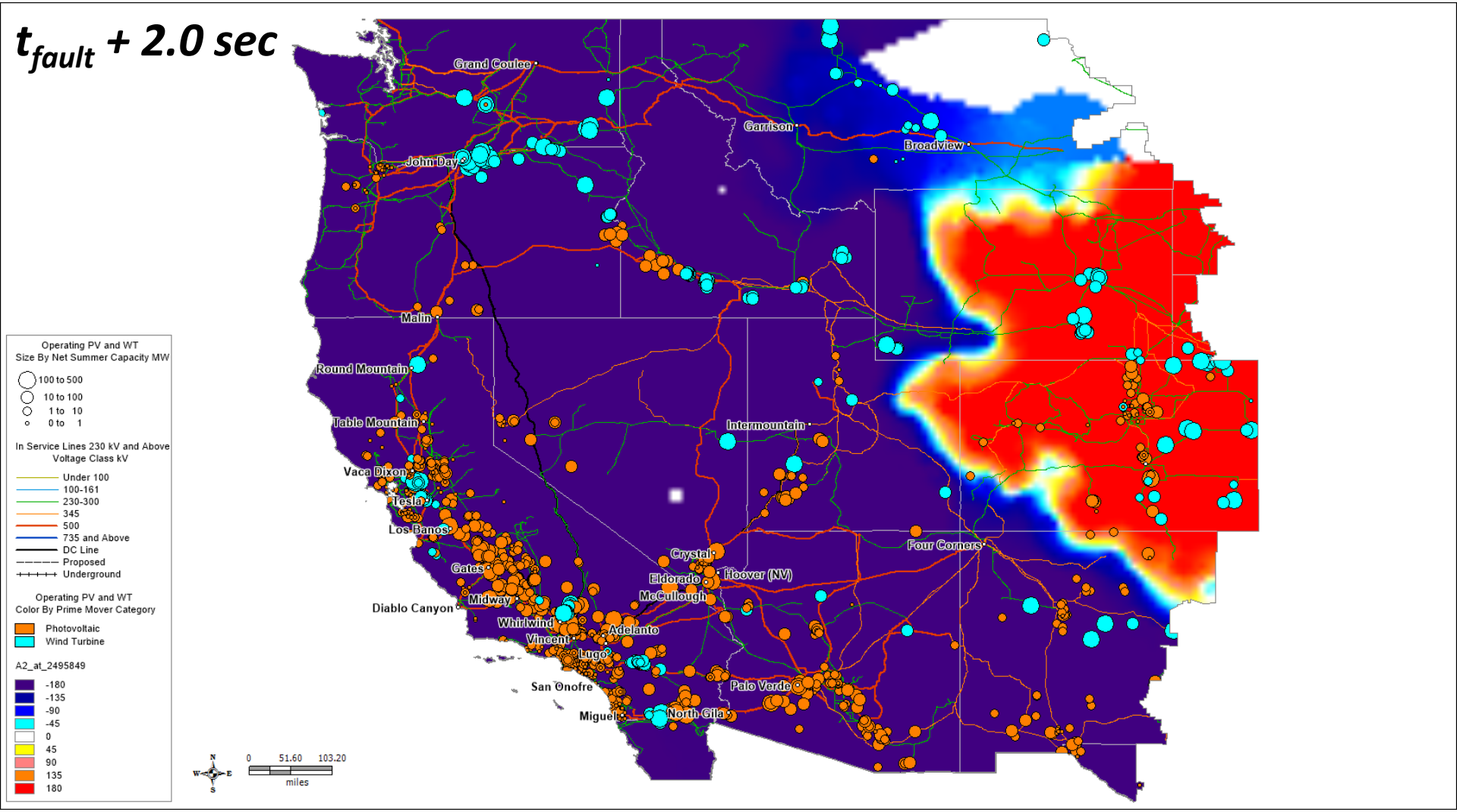


Clarification and Recommendation for Momentary Cessation

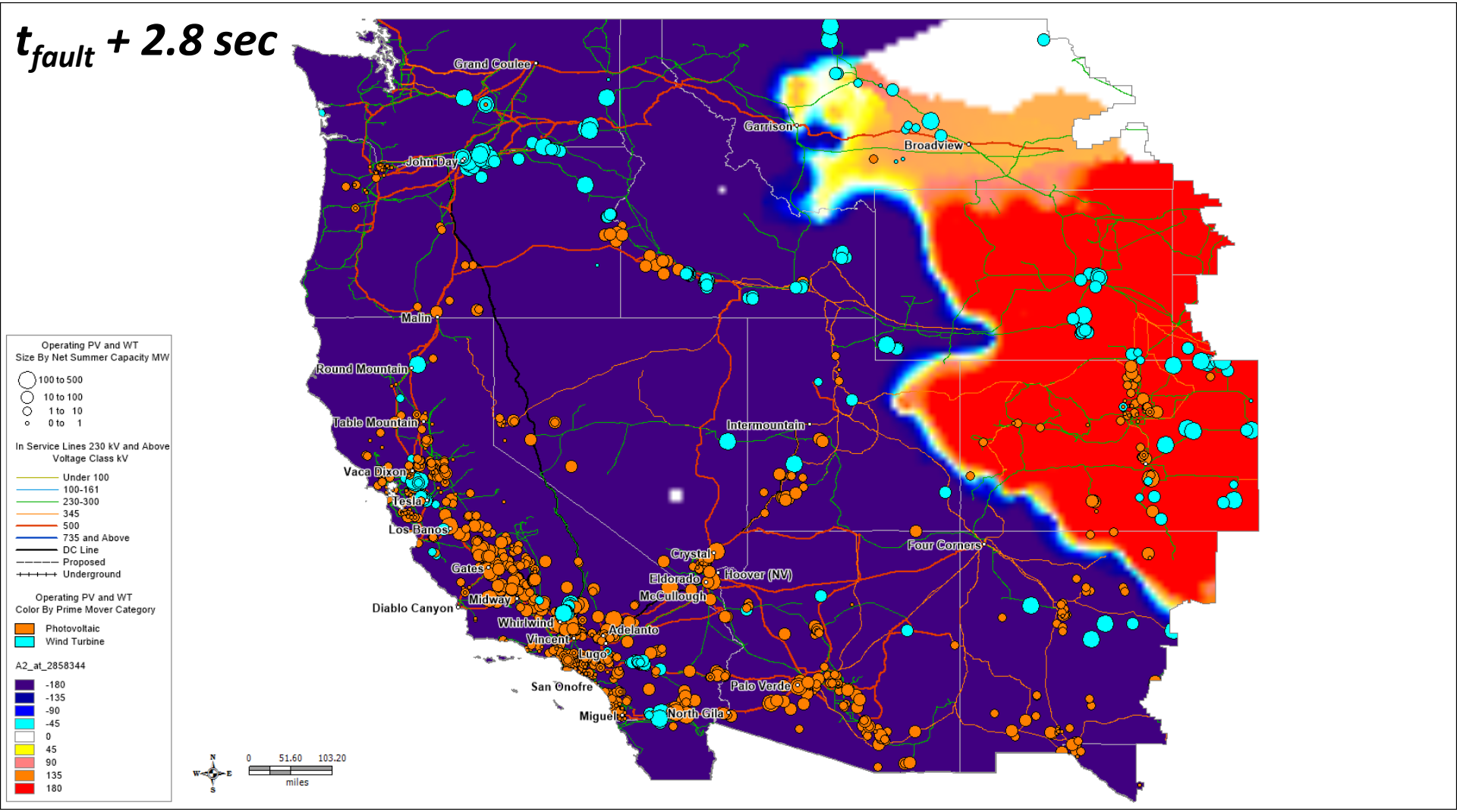
t_{fault} + 1.5 sec



Clarification and Recommendation for Momentary Cessation



Clarification and Recommendation for Momentary Cessation

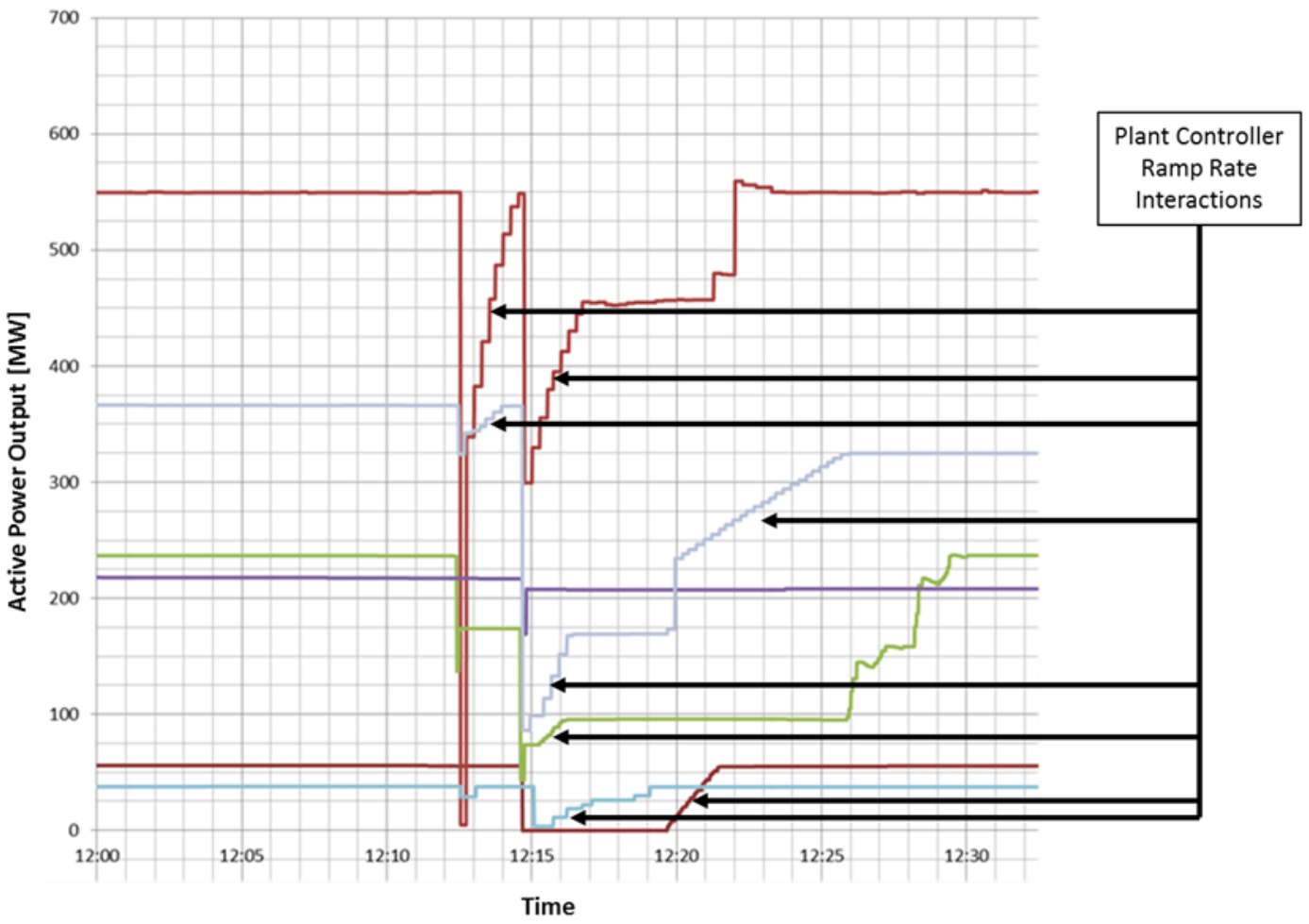


Momentary Cessation Recommendation Moving Forward

- Generator Owners should coordinate with their inverter manufacturer(s) to **eliminate momentary cessation (MC) to the greatest extent possible**.
- For inverters where MC cannot be eliminated (e.g., use another form of ride-through mode), MC settings should be changed by:
  - Reducing the MC low voltage threshold to the lowest value possible.
  - Reducing the recovery delay to the smallest value possible (e.g., on the order of 1-3 electrical cycles).
  - Increasing the active power ramp rate to at least 100% per second (e.g., return to pre-disturbance active current injection within 1 second).
  - Setting reactive current priority upon recovery (if applicable) should eliminate the use of MC on all inverters that are capable of continuous current injection during abnormal voltages.

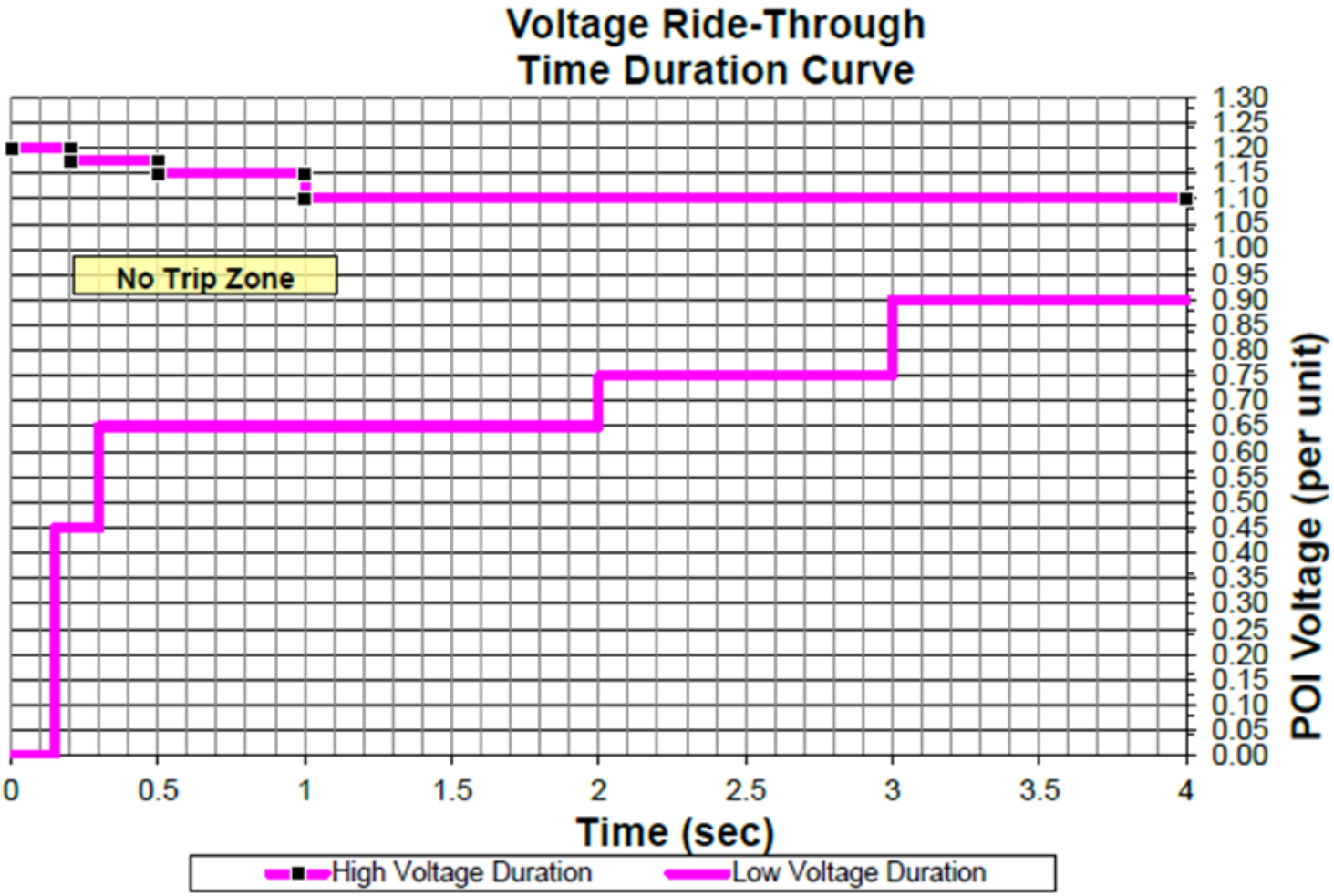
Key Findings #3

Ramp rate interactions with return from momentary cessation



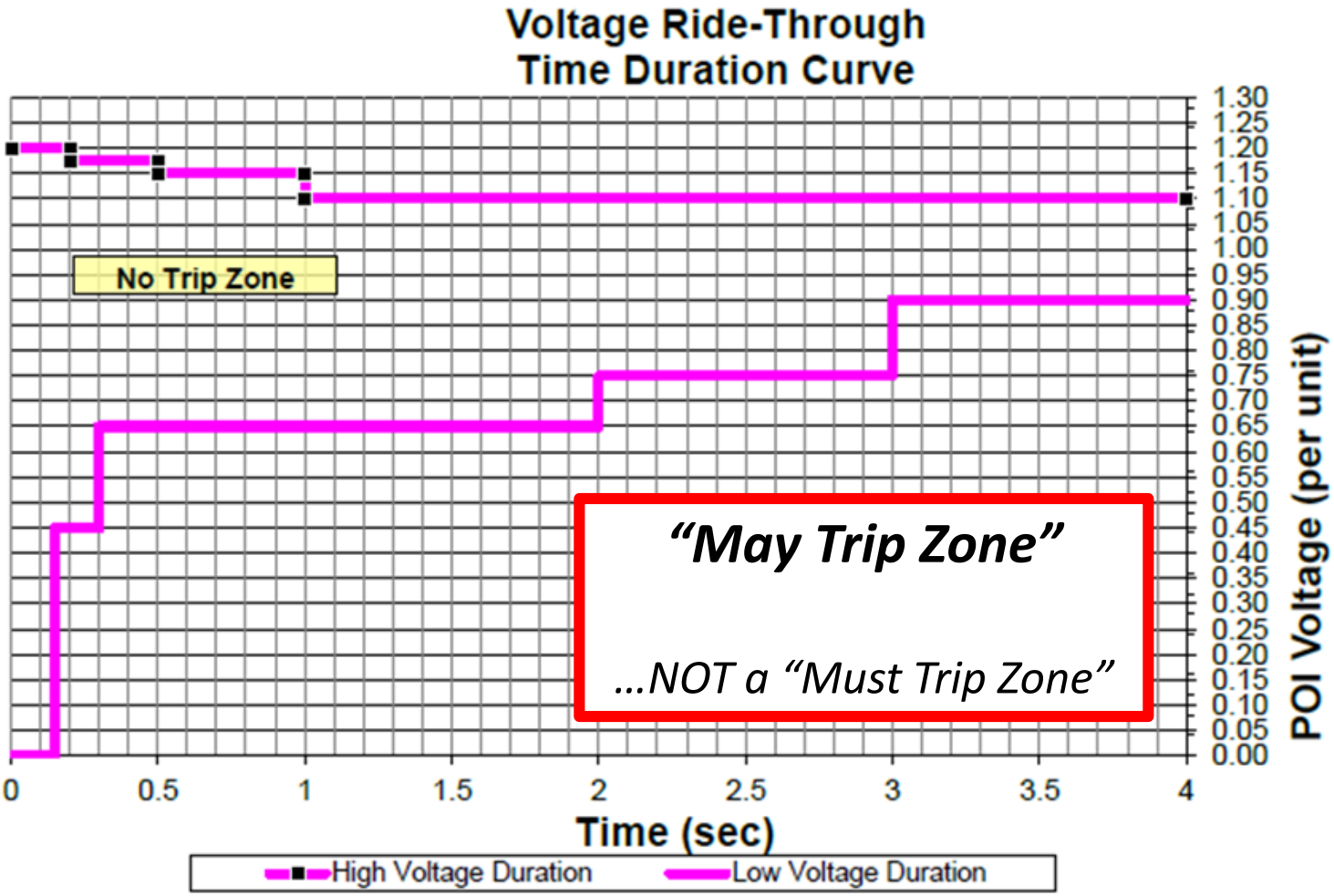
Key Findings #4

Interpretation of PRC-024-2 voltage ride-through curve



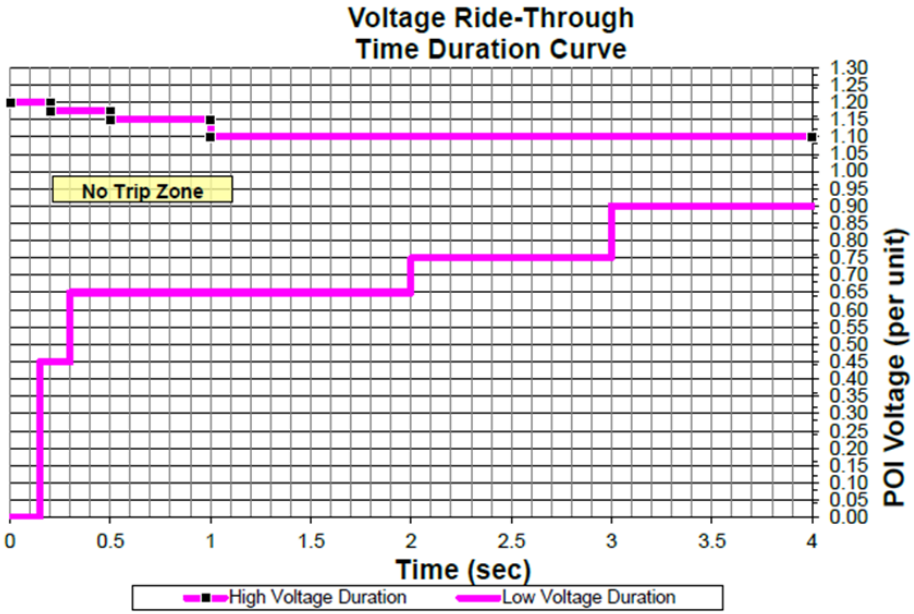
Key Findings #4 Clarification 1

Interpretation of PRC-024-2 voltage ride-through curve



Key Findings #4 Clarification 2

Interpretation of PRC-024-2 voltage ride-through curve



This curve is a minimum requirement.

This curves should NOT be a design criteria.

Protection should be set based on equipment limitations.

Equipment should be designed as robust as possible.

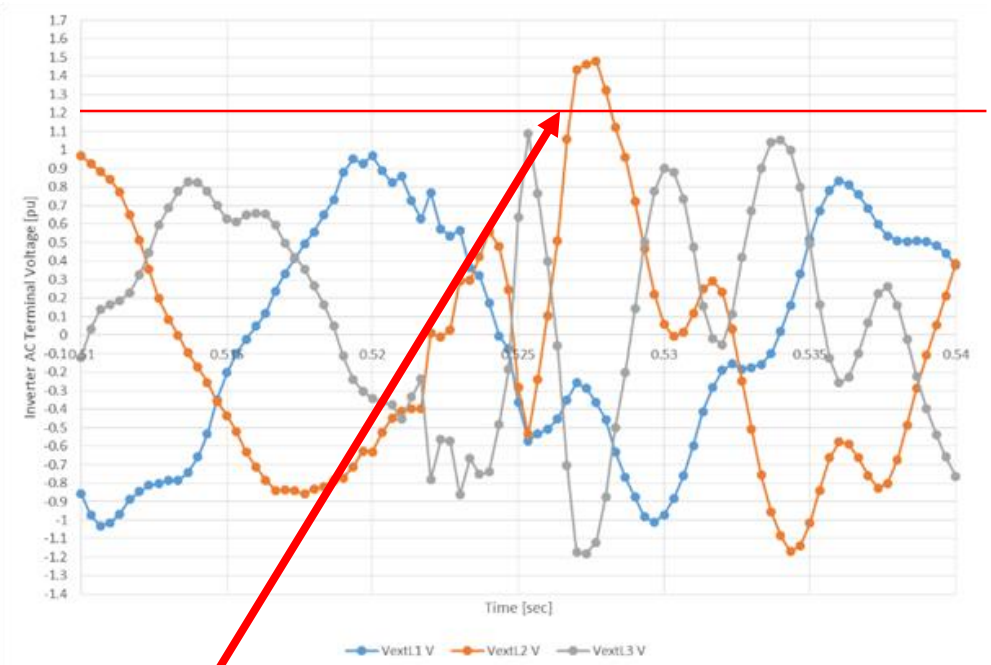
Key Findings #4 Clarification 3

Interpretation of PRC-024-2 voltage ride-through curve

- **Requirement R2:** Each Generator Owner that has generator voltage protective relaying1 activated to trip its applicable generating unit(s) shall set its protective relaying such that the generator voltage protective relaying does not trip the applicable generating unit(s) as a result of a voltage excursion (at the point of interconnection[3]) caused by an event on the transmission system external to the generating plant that remains within the "no trip zone" of PRC-024 Attachment 2.
- **Footnote 3:** For the purposes of this standard, point of interconnection means the transmission (high voltage) side of the generator step-up or collector transformer.

Key Findings #5

Instantaneous voltage tripping and measurement filtering

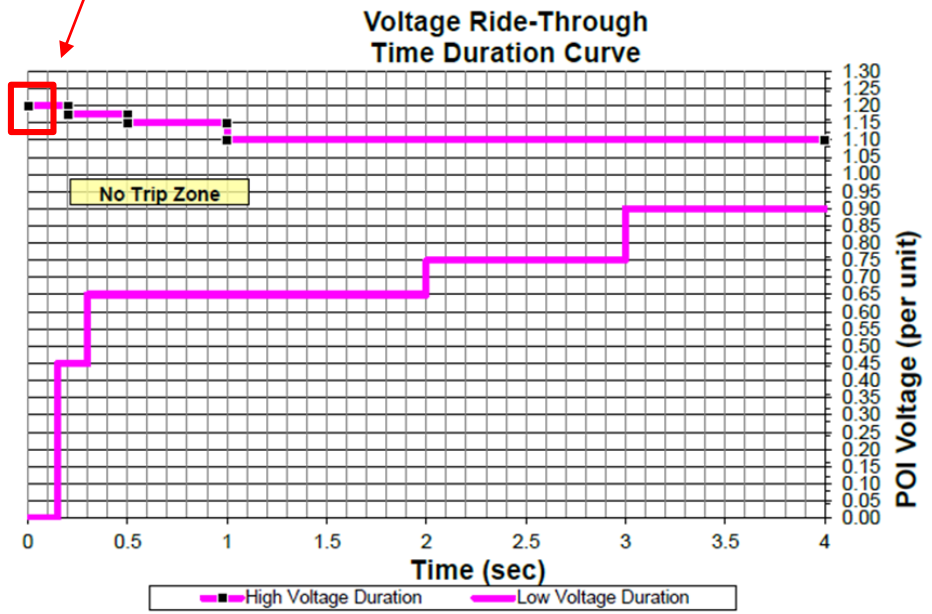


Inst. Voltage [pu nominal peak]	Samples	Time [sec]	Cycles
> 1.1	5	0.00167	0.1
> 1.2	4	0.00133	0.08
> 1.3	4	0.00133	0.08
> 1.4	3	0.00100	0.06

Key Findings #5

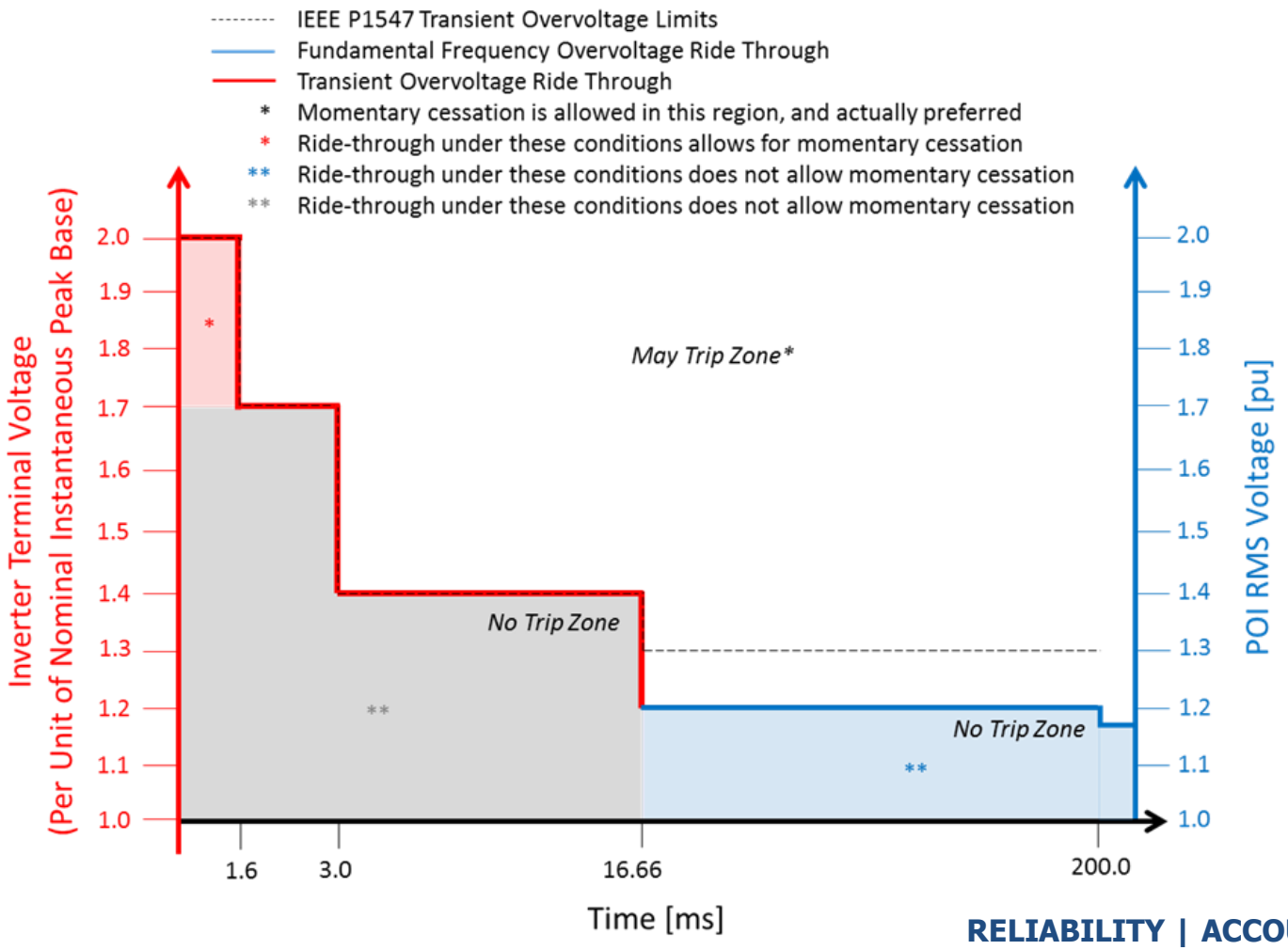
Instantaneous voltage tripping and measurement filtering

High Voltage Ride Through Duration		Low Voltage Ride Through Duration	
Voltage (pu)	Time (sec)	Voltage (pu)	Time (sec)
≥ 1.20	Instantaneous Trip	≤ 0.45	0.15
≥ 1.175	0.20	≤ 0.65	0.30
≥ 1.15	0.50	≤ 0.75	2.00
≥ 1.10	1.00	≤ 0.90	3.00



Key Findings #5
IRPTF Recommended HVRT

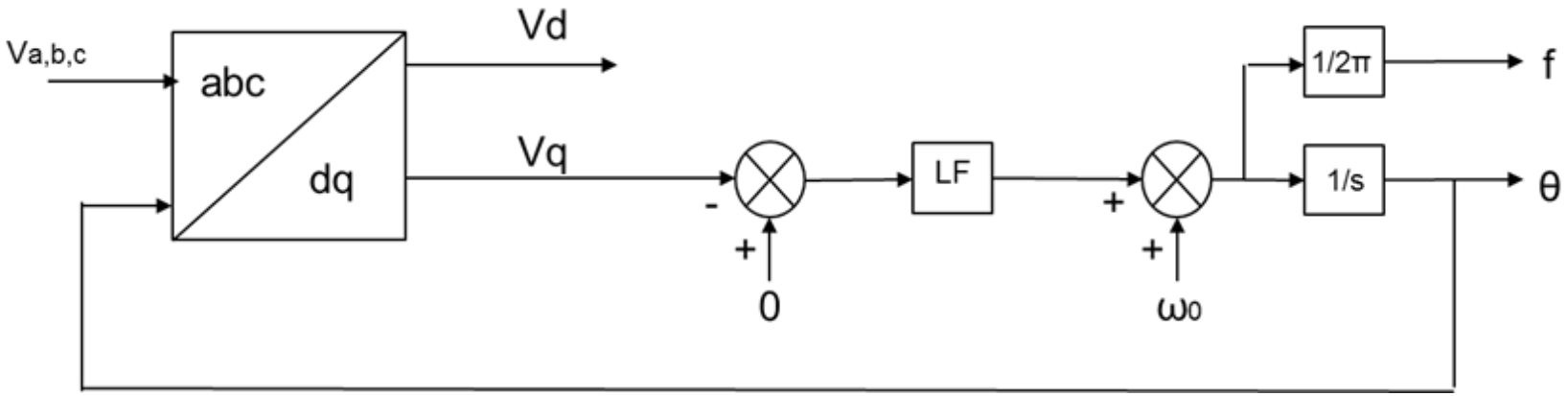
Instantaneous voltage tripping and measurement filtering



Key Findings #6

Phase lock loop synchronization issues

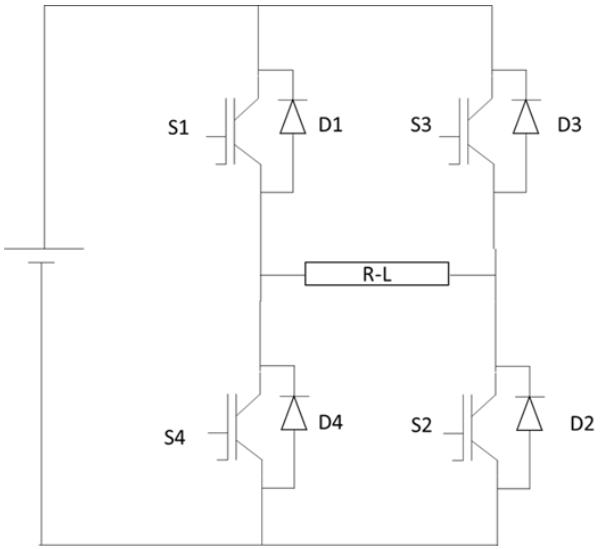
- Grid voltage phase jumps occur (e.g., during faults)
- Inverter PLLs should be robust to withstand BPS phase jumps
- Should not result in inverter tripping or momentary cessation
- Advanced controls should enable “PLL ride-through” rather than tripping

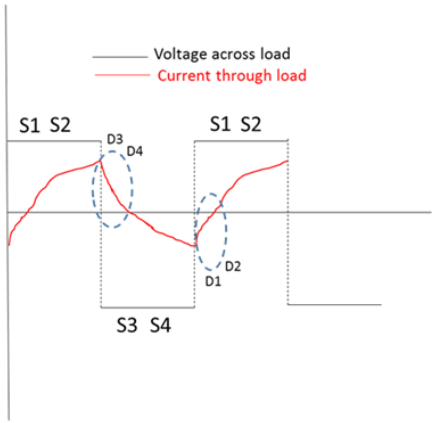


Key Findings #7

DC reverse current tripping

- Anti-parallel diodes dissipate energy, mitigate voltage spikes
- Can conduct if forward biased (AC voltage > DC voltage)
- UL 1741 requires testing and detection, no specified trip settings
- DC reverse current detection protects panels, not inverter
- Very sensitive settings for one plant

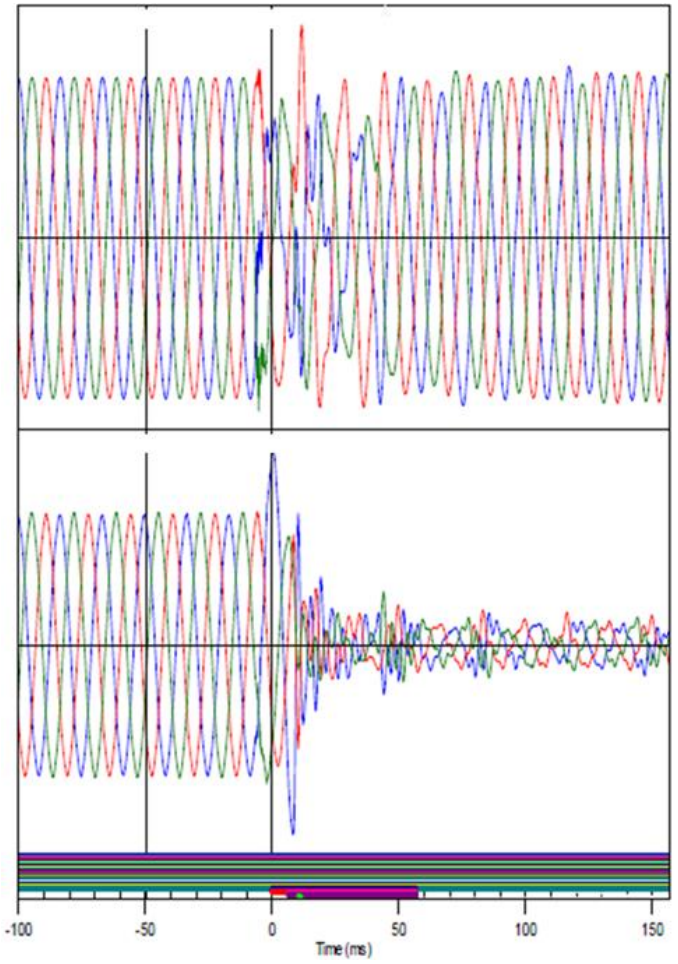




Key Findings #8

Transient interactions and ride-through considerations

- Interactions between momentary cessation, in-plant shunt capacitors, transient voltages, harmonics, etc., that are not sufficient understood
- Requires detailed electromagnetic transient (EMT) studies needed



Next Steps and Future Work

- Disturbance Report to be published in February 2018
- NERC Alert to be published in likely March 2018
  - Mitigation of momentary cessation
  - Voltage protective control functions
  - PRC-024-2 curve interpretation
  - Transient overvoltage settings
- IRPTF will be publishing a Reliability Guideline on Inverter-Based Resources Performance in Q3 or Q4 2018

Relevant Links

- Blue Cut Fire Disturbance Report: http://www.nerc.com/pa/rrm/ea/Pages/1200-MW-Fault-Induced-Solar-Photovoltaic-Resource-Interruption-Disturbance-Report.aspx
- EA Page (for future Disturbance Report): http://www.nerc.com/pa/rrm/ea/Pages/default.aspx
- NERC Alerts Page: http://www.nerc.com/pa/rrm/bpsa/Pages/Alerts.aspx
- IRPTF Page: http://www.nerc.com/comm/PC/Pages/Inverter-Based-Resource-Performance-Task-Force.aspx

Questions and Answers

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