NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Engineering the Changing Resource Mix

Keeping the Grid Together

Robert W. Cummings
NERC Senior Director of Engineering and Reliability Initiatives
CURENT – University of Tennessee Knoxville
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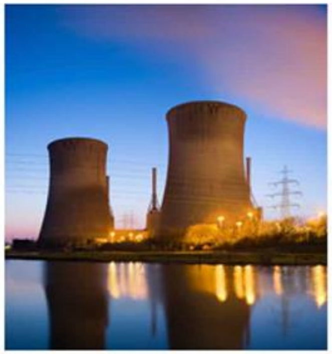
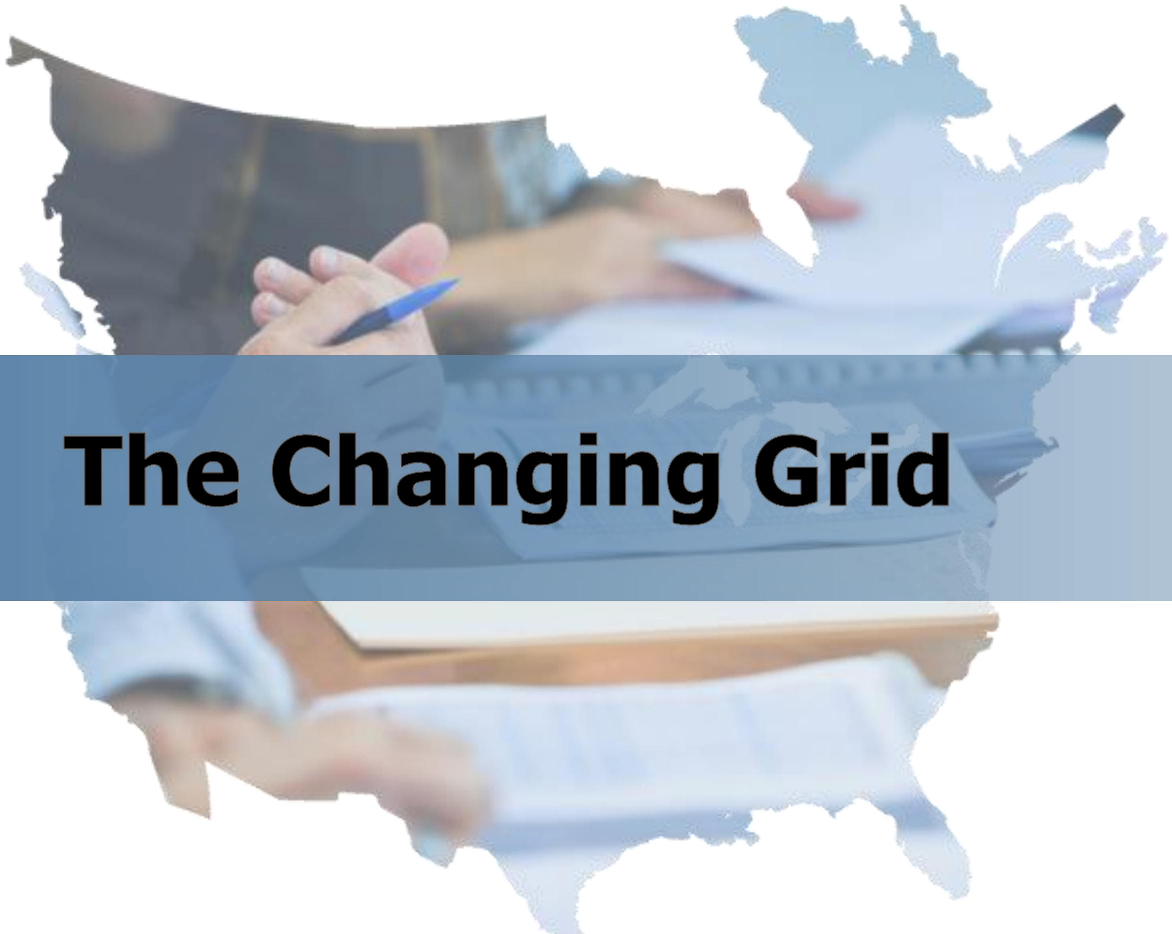
RELIABILITY | ACCOUNTABILITY



The Changing Grid

Changing Load

- Load composition changing
  - Electric vehicle charging
  - LED lighting
  - Variable speed drive motors
- Distributed Energy Resources
  - Inverter-based resources
    - Roof-top solar panels
    - Micro turbines
    - Small wind turbines
- Load becoming schizophrenic
  - Load models no longer adequate for simulations

Changing Resources

Changing Dispatch Mix

- High penetration of renewables – variable resources
- Minimum generation levels on conventional units
- Ramping needs increase for load following

Retirement of large fossil-fired generation plants

- Loss of dynamic reactive support for voltage control
- Possible reduced system inertia
- Lower levels of synchronizing torque

Changing System Inertia

- Trade-offs between inertia and Primary Frequency Response

Cautionary Tales

Inadvertent creation of new reliability hazards

- Very large DC transmission projects
  - New largest single hazards??

Series-compensated transmission lines

- Sub-synchronous resonance
- Sub-synchronous controls interaction
  - Inverter-based resources
  - Digital controls on conventional generation
  - System controls – SVCs, Statcoms, DC converter stations, etc.

Fault-induced Inverter Controls – voltage and frequency ried-through

Potential Interaction Examples

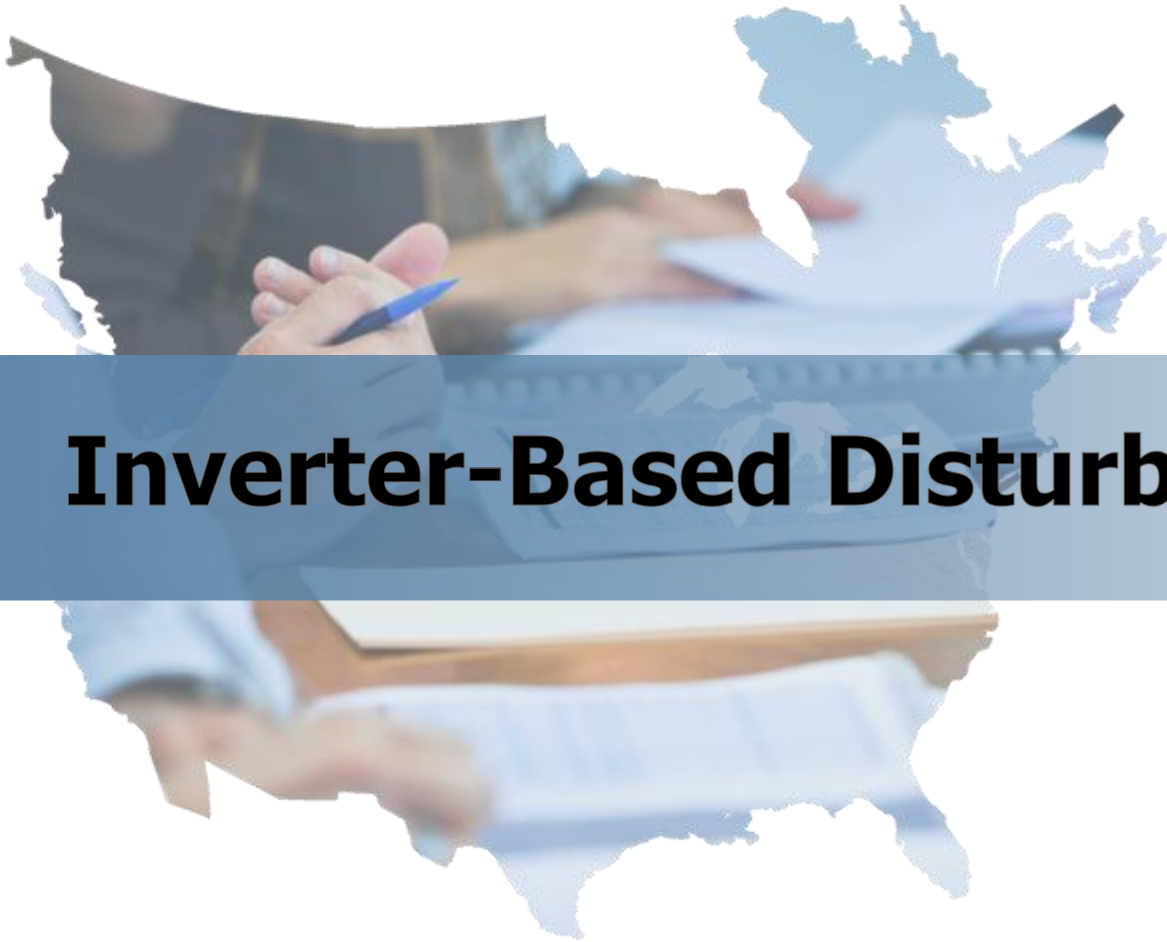
Potential response to combination of voltage and frequency perturbations associated with complex system disturbances

High-quality supply loads that are Voltage/Frequency-sensitive

- Experience of 600 to 900 MW load loss due to transfers to backup supplies during faults

Locational injection impact on transmission elements and interfaces

- Response masquerading as a power swings – protection system concerns



Inverter-Based Disturbance

August 16, 2016 Faults

Blue Cut fire caused

- Thirteen 500 kV line faults
- Two 287 kV line faults

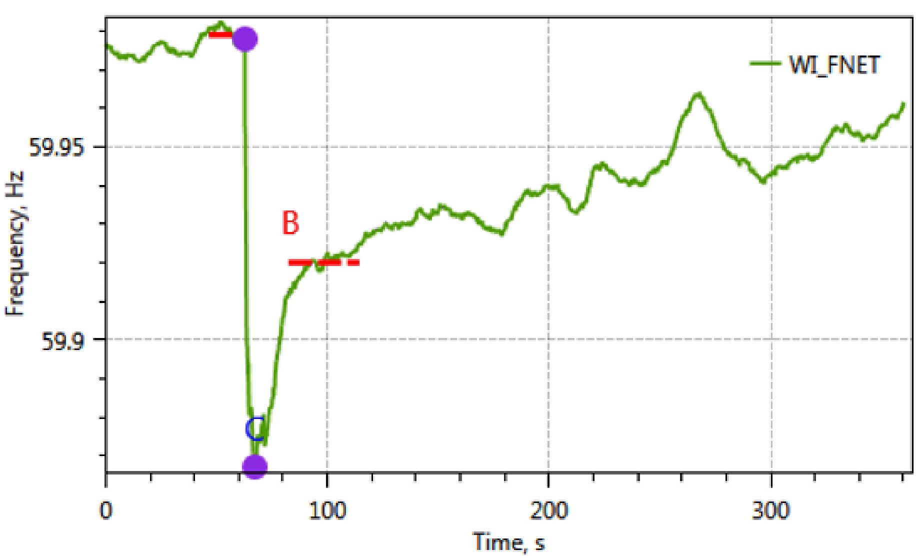
11:45:06 PDT Fault

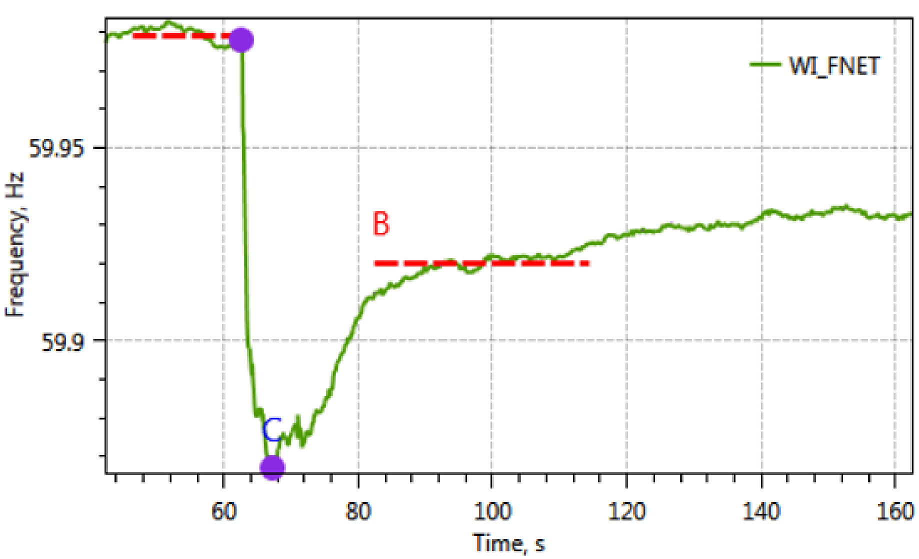
- 500 kV line-to-line fault
- Cleared normally in 2.5 cycles (41.7 milliseconds)
- PV resources impacted – 1,178 MW
  - 26 different solar developments
  - All utility scale – connected at 500kV or 230kV
  - 10 different inverter manufacturers
  - No PV site system protection relays/breakers operated
  - All action was by on-board inverter controls

Western Interconnection Frequency

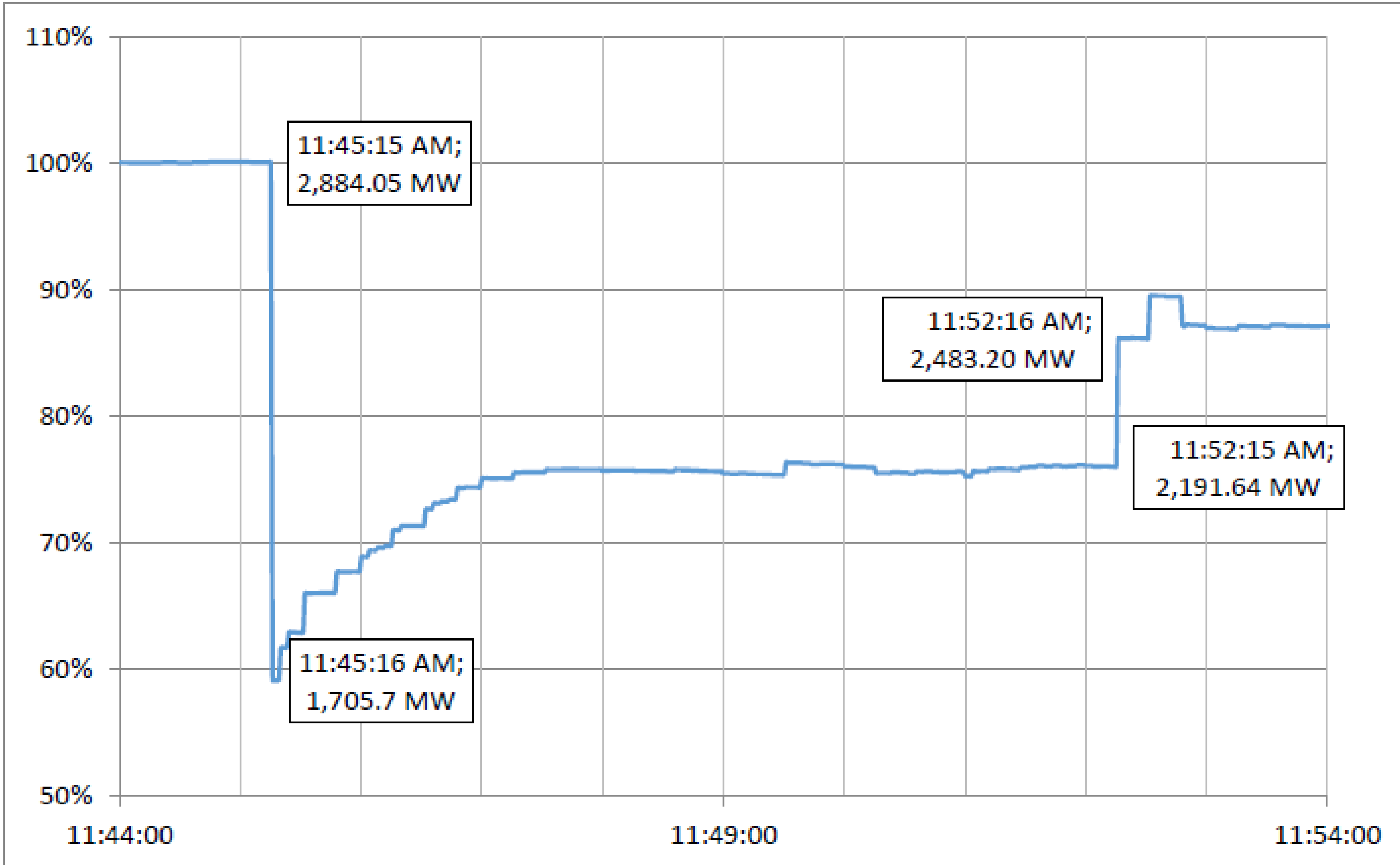
WI_20160816_184506

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





Solar Resource Loss



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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
12	06/15/2017					

16 August 2016 Line-to-Line Fault

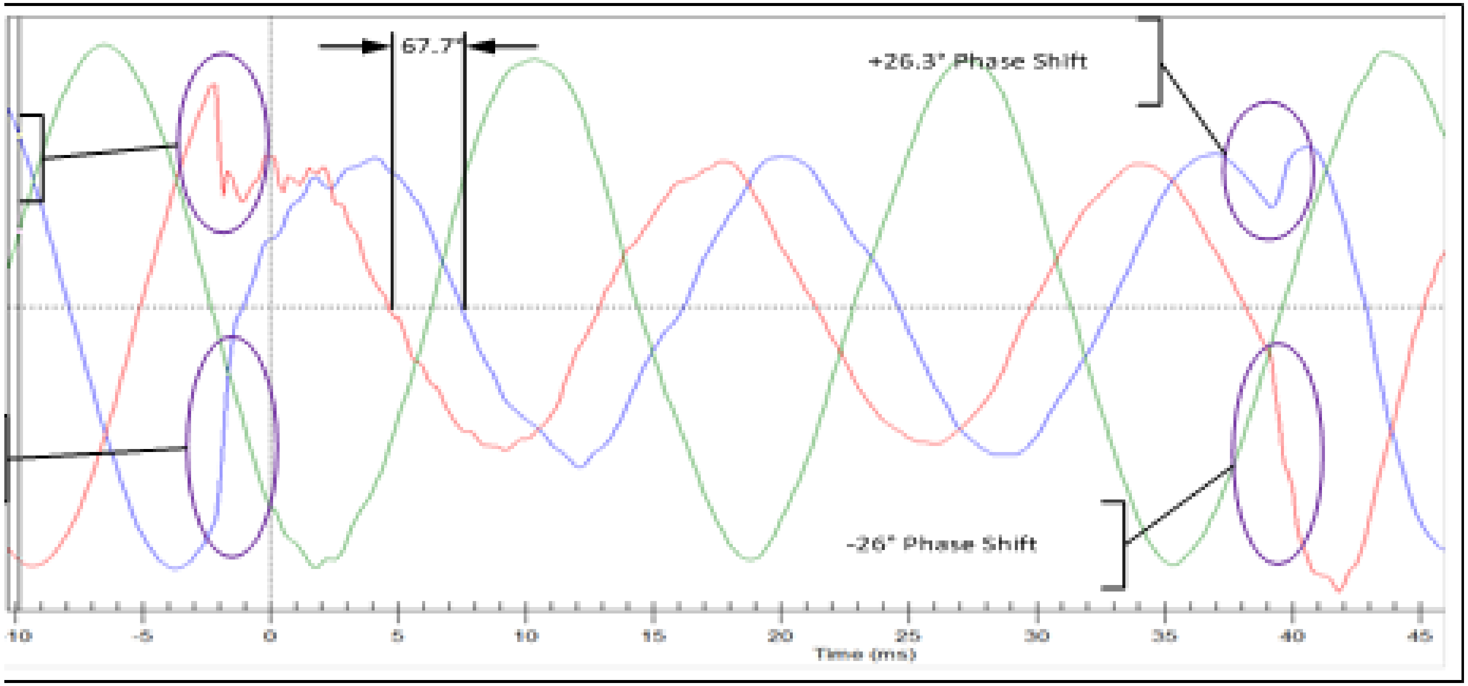
- 26 different solar developments
- All utility scale
- Majority connected at 500kV or 230kV
- 10 different inverter manufacturers
- Reported causes of “trips”
  - Under frequency
  - Under voltage
  - Over voltage
  - DC overcurrent
  - 1 loss of synchronism

PV Inverter Operating Modes

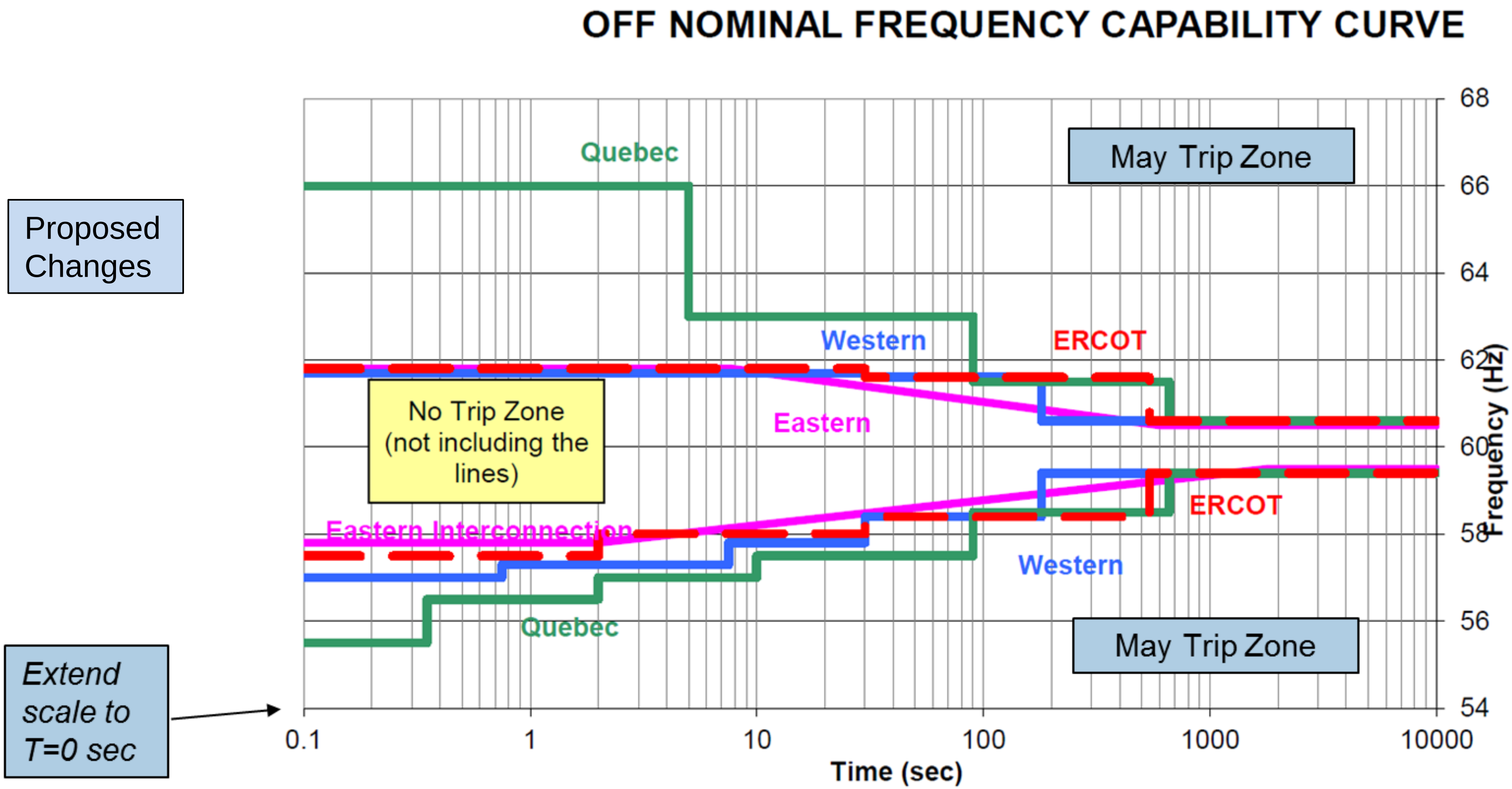
- **Continuous Operation** – Actively injecting current into the grid
- **Momentary Cessation** – Momentarily cease injecting active current into the grid, but remain electrically connected
  - Triggered by abnormal system voltages (< 0.9 or > 1.1 per unit)
- **Trip Mode (Cease to Energize)** – Ceased injecting current and will delay returning to service. (typically 5 minute delay)
  - May also mechanically disconnect from the grid

Phase Shift or Phase Jump

- A phase-to-phase fault caused the voltage phasors to deviate from their normal 120° separation (a.k.a., Phase Jump)
- Occurs at fault inception and at fault clearing
  - The time domain shows the phase separation decreased when the fault occurred and shifted back when the fault cleared

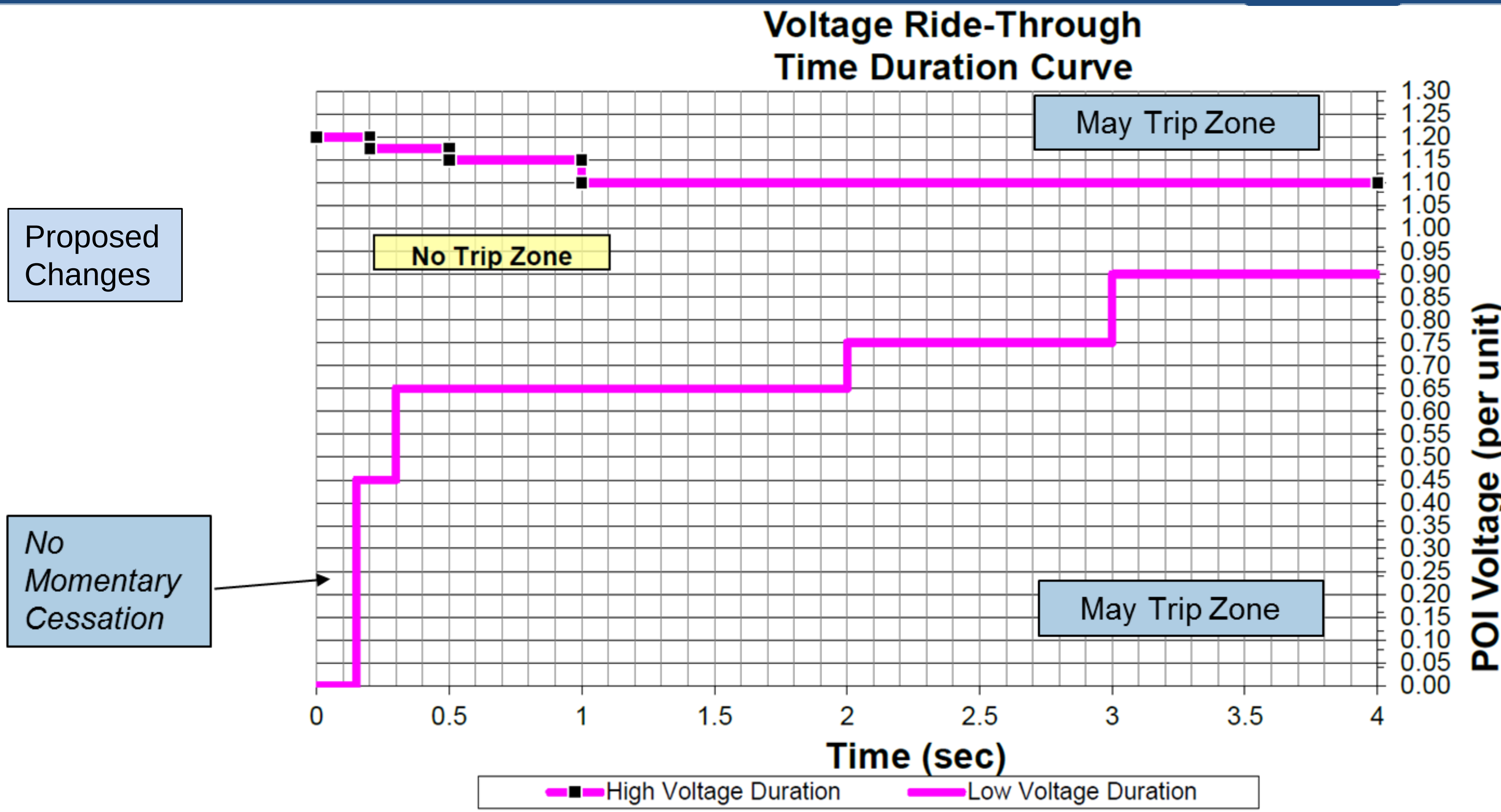


Potential Revisions to PRC-024



- Do not disconnect, no “Momentary Cessation” in No Trip zone
- Frequency calculated as f over time window (0.1 sec)

Potential Revisions to PRC-024 on Voltage Ride-through



- No "Momentary Cessation" within in No Trip Zone
- "May Trip" (to protect equipment) instead of Must Trip outside of No Trip Zone
- Expectation to support grid, supplying current during fault

What's been done?

- Inverter-Based Resource Performance Task Force (IRPTF)
  - Task Force expanded and scope extended
  - Reporting to both NERC Operating and Planning Committees
- Frequency tripping
  - Manufacturers are adding tripping delay for frequency trips
- Voltage ride-through
  - Simulations to identify momentary cessation risk
  - Initial analysis showed significant resources potentially at risk for low voltage problems
  - Specify maximum delay and ramp rate for Restore Output
  - Additional simulations and analysis ongoing

Ongoing Work

NERC is continuing the ongoing work to achieve a cohesive inverter-based resource performance:

- Collaboration with Standard IEEE 1547 and 1547.1 covering distribution level DER
- Collaborating with the new IEEE *Integration of Renewable Energy into Transmission and Distribution Grids Subcommittee*, which reports to the IEEE PES Energy Development and Power Generation Committee – addressing the DER connected above distribution voltage but below transmission voltages
- Considering the recommended changes to NERC Standards recommended in the *1,200 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance* report of the NERC/WECC Inverter Task Force – BPS connected inverter resources

Report & Alert Available on NERC Website

http://www.nerc.com/pa/rrm/bpsa/Pages/Alerts.aspx

- **Event Analysis Report released 8 June 2017:**

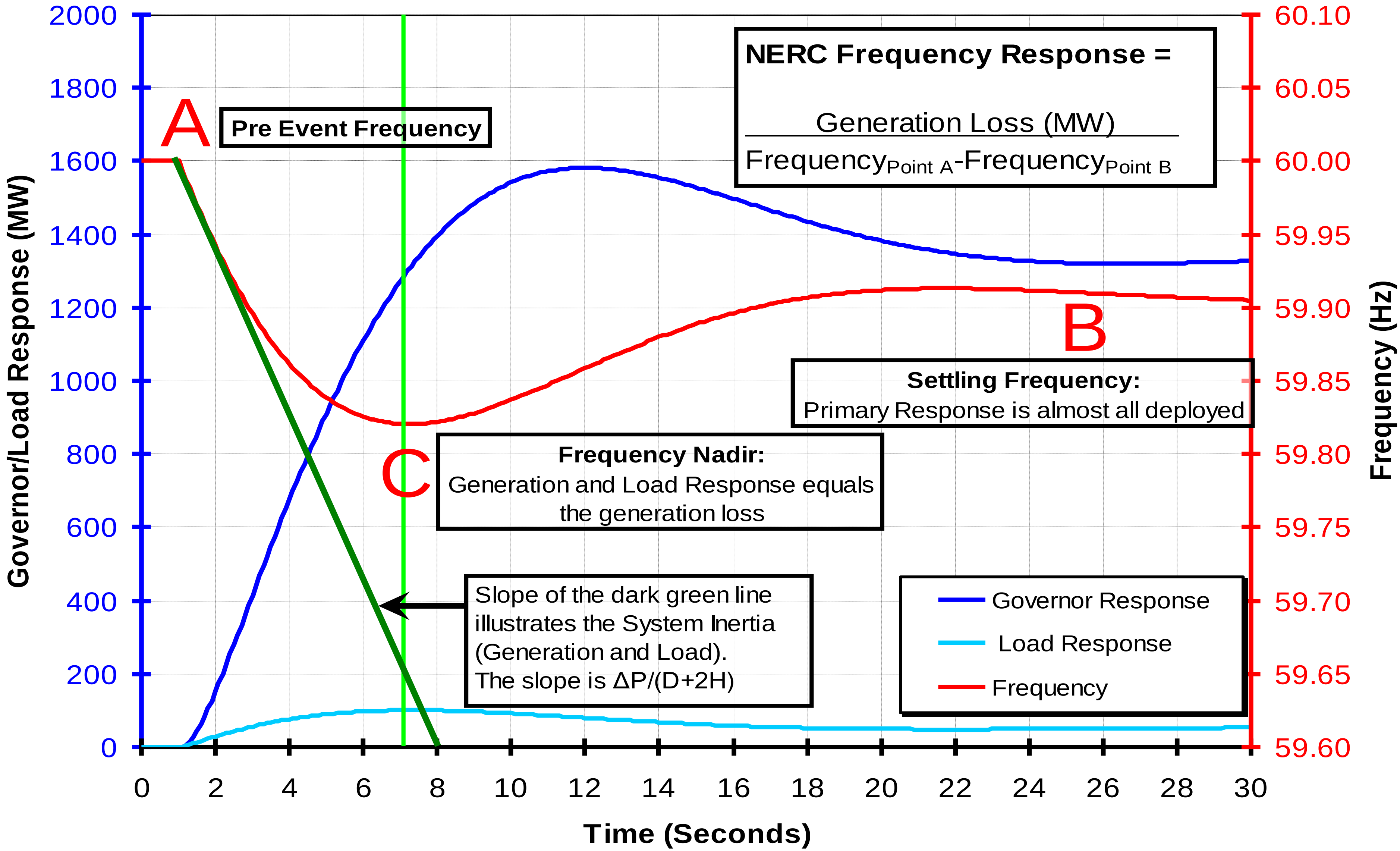
1200 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance report

- **Alert – Industry Recommendation issued 20 June 2017:**

Loss of Solar Resources during Transmission Disturbances due to Inverter Settings

Changing Inertia & Frequency Response

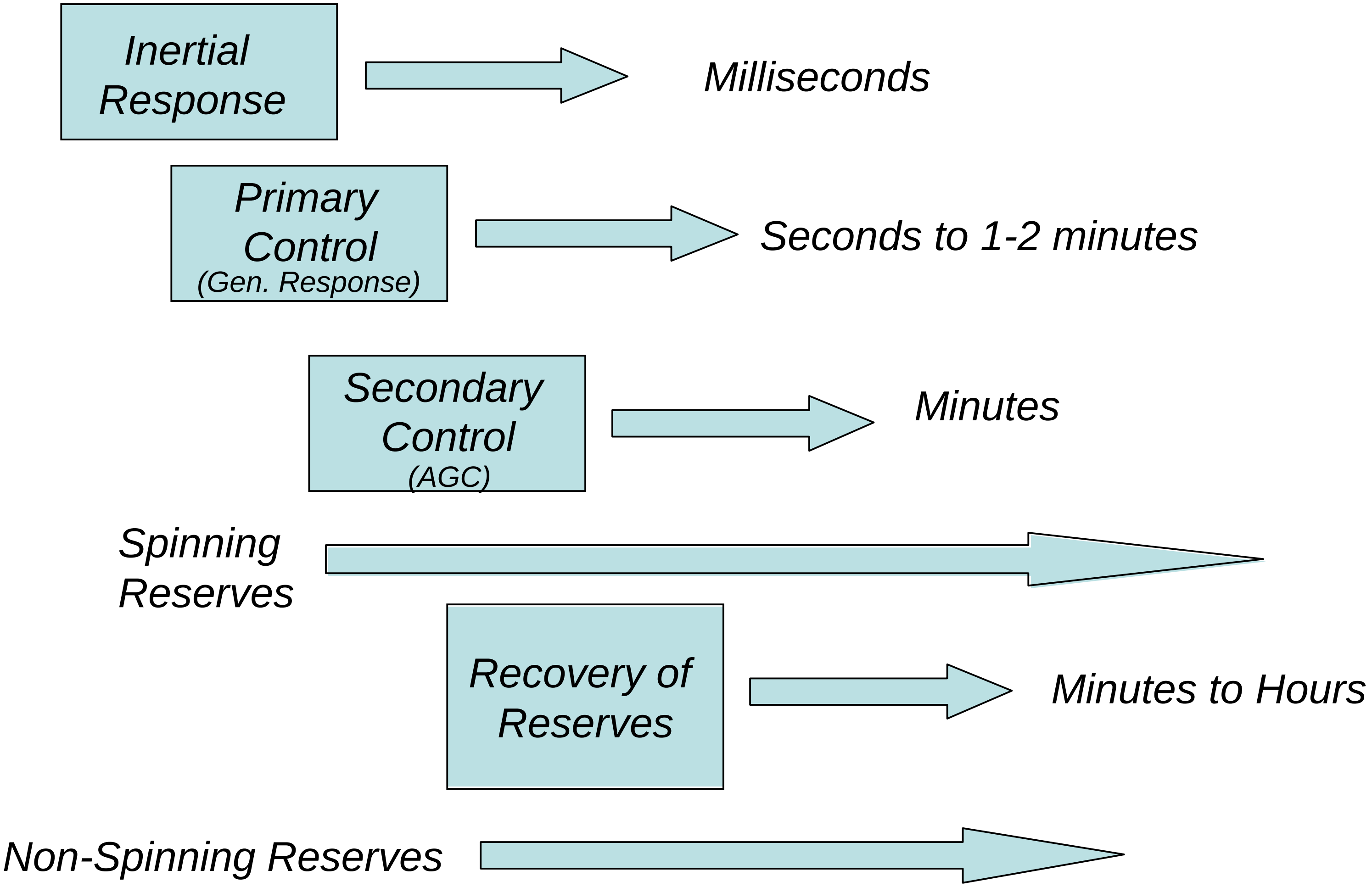
Frequency Response Basics



Frequency Response Strategy

- All resources should have the ***capability*** of providing Primary Frequency Response
  - Regardless of dispatch, frequency response should be available
  - Comments to FERC on SGIA and LGIA
- Create a continuum of frequency response based on capabilities of specific resources:
  - Arresting energy injection from fast frequency response from storage and modulated load
  - Contracting for frequency responsive loads
  - Sustained response from conventional generation resources and modulated load
- Cohesive Frequency Response regulations
  - IEEE 1547
  - NERC PRC-024

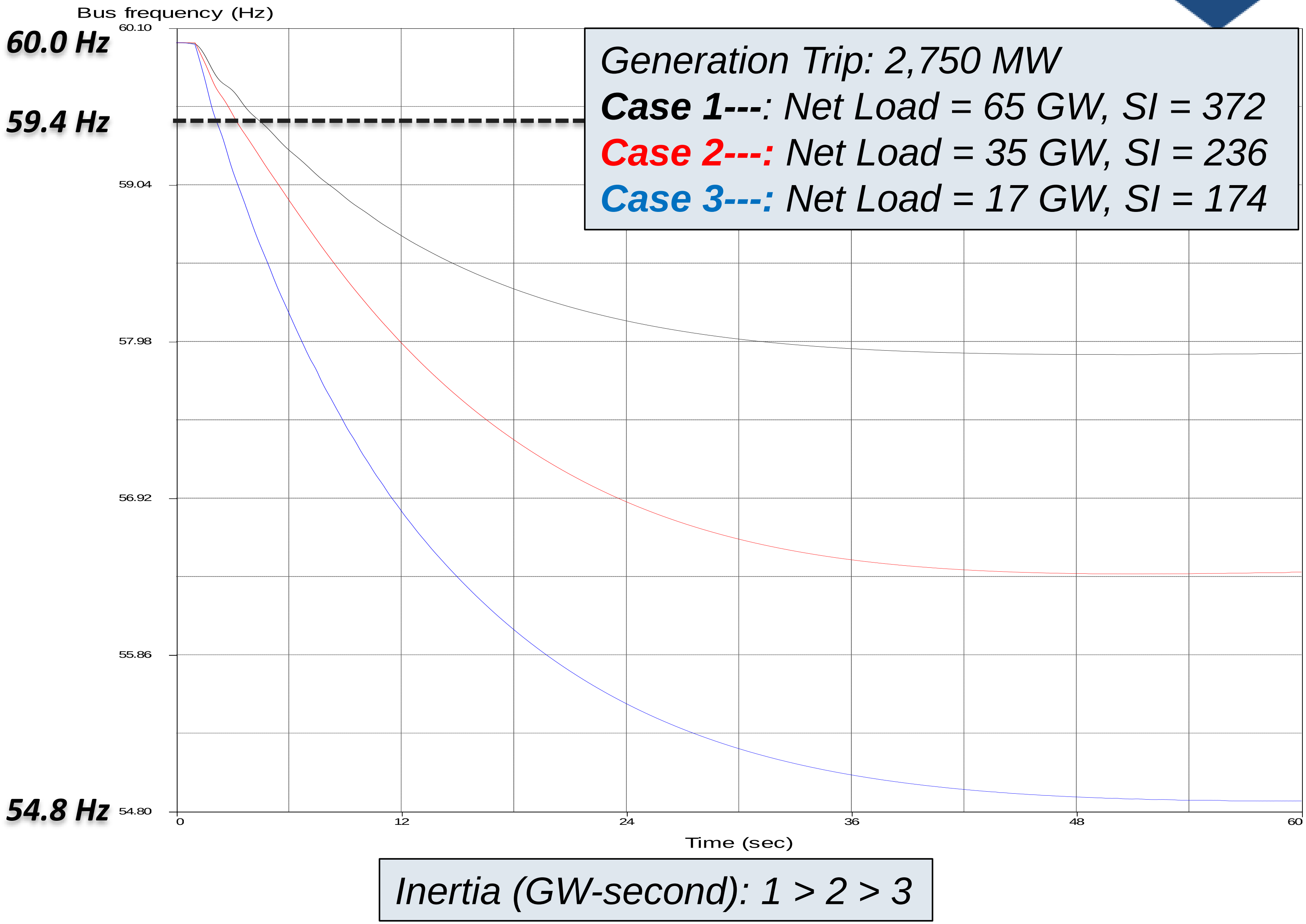
Frequency Response Control Continuum



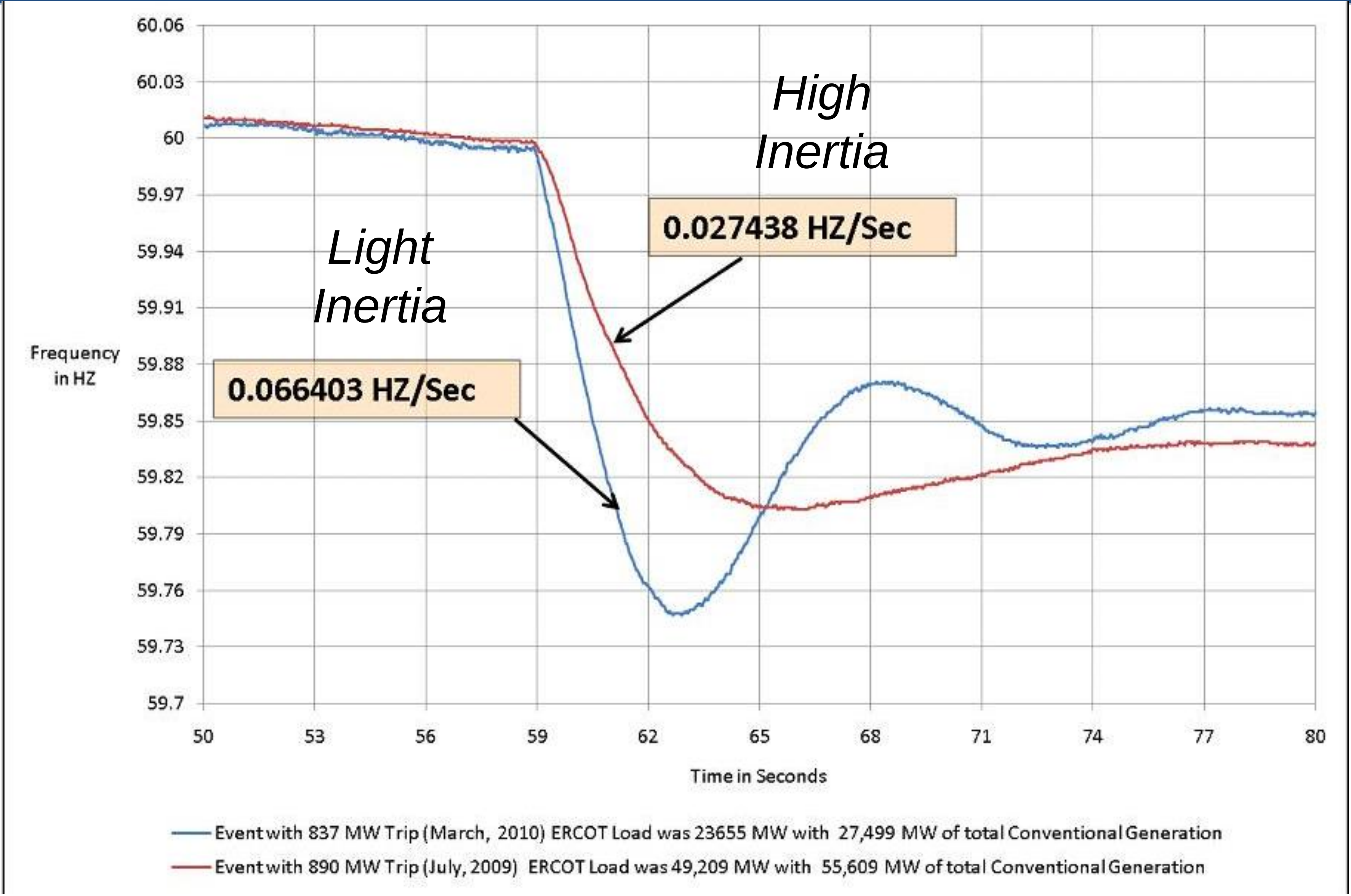
Potential Sources of Primary Frequency Response

- Traditional generation
- Wind Turbines
  - "Synthetic Inertia"
  - Off-optimal blade attack angle – backing down from maximum
- Energy Storage
- Distributed Energy Resources
  - Solar
  - Micro turbines
  - Micro grid resources
- Load acting as a resource
  - Tripped by specialized under-frequency relays
  - Smart appliances – independent operation
  - Aggregated load – controlled by aggregator
  - "Modulated load"

Importance of System Inertia in ERCOT



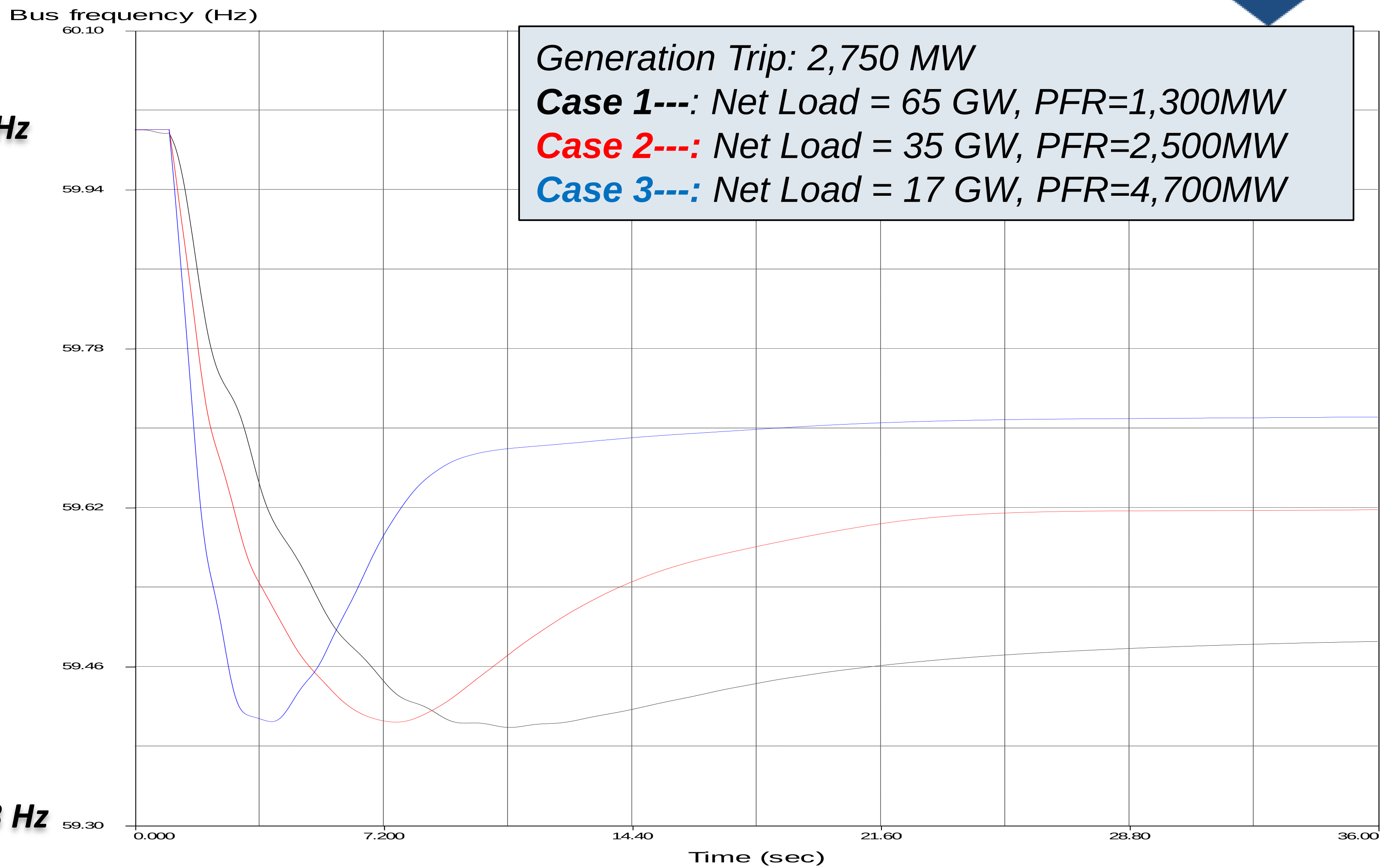
Inertial Response Variability



Trade-off between Inertia and Primary Frequency Response

60.0 Hz

59.3 Hz



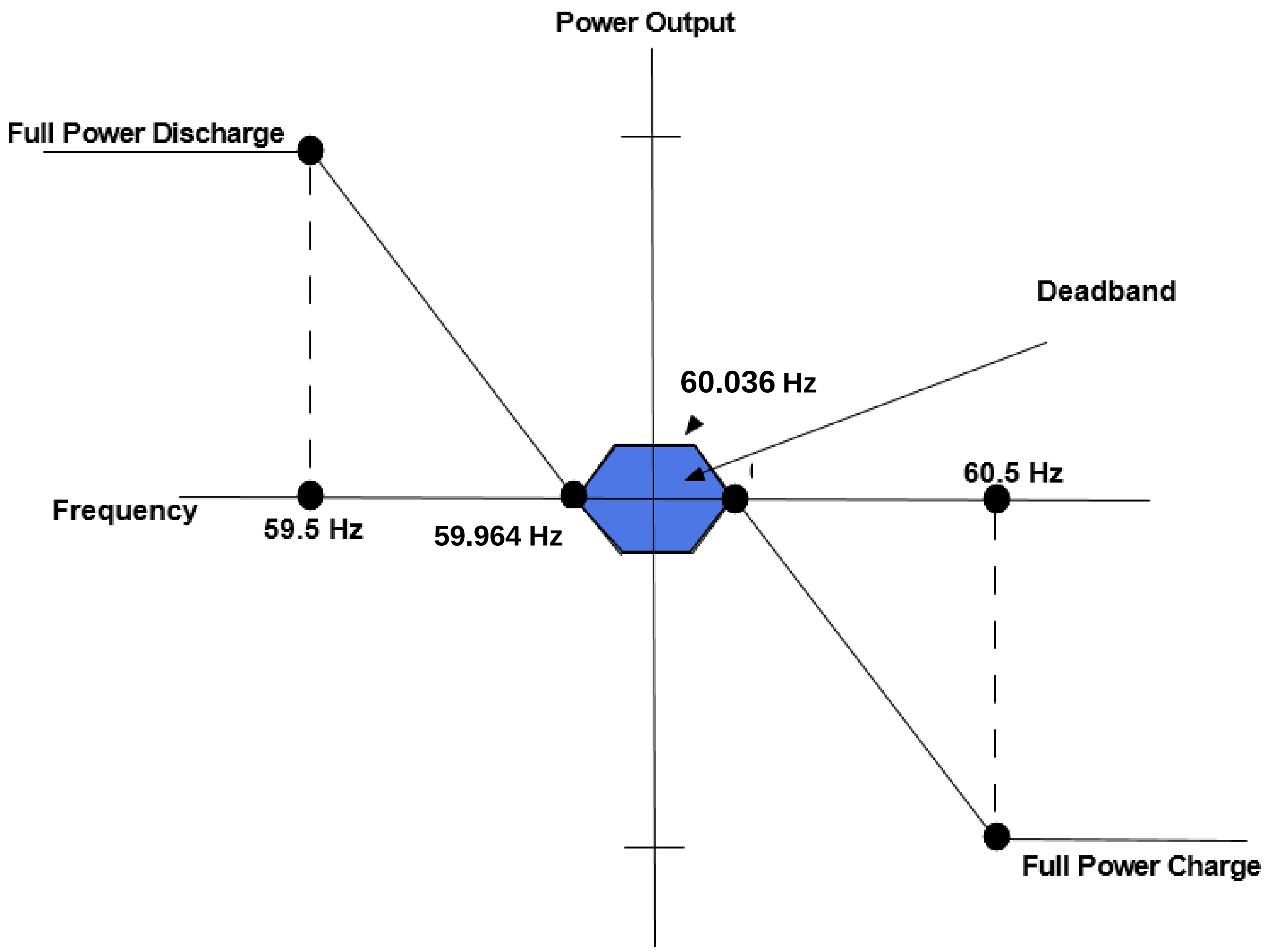
Primary Frequency Response (MW): 3 > 2 > 1

Potential Roles of Energy Storage

Multiple Roles for Energy Storage in Maintaining Reliability

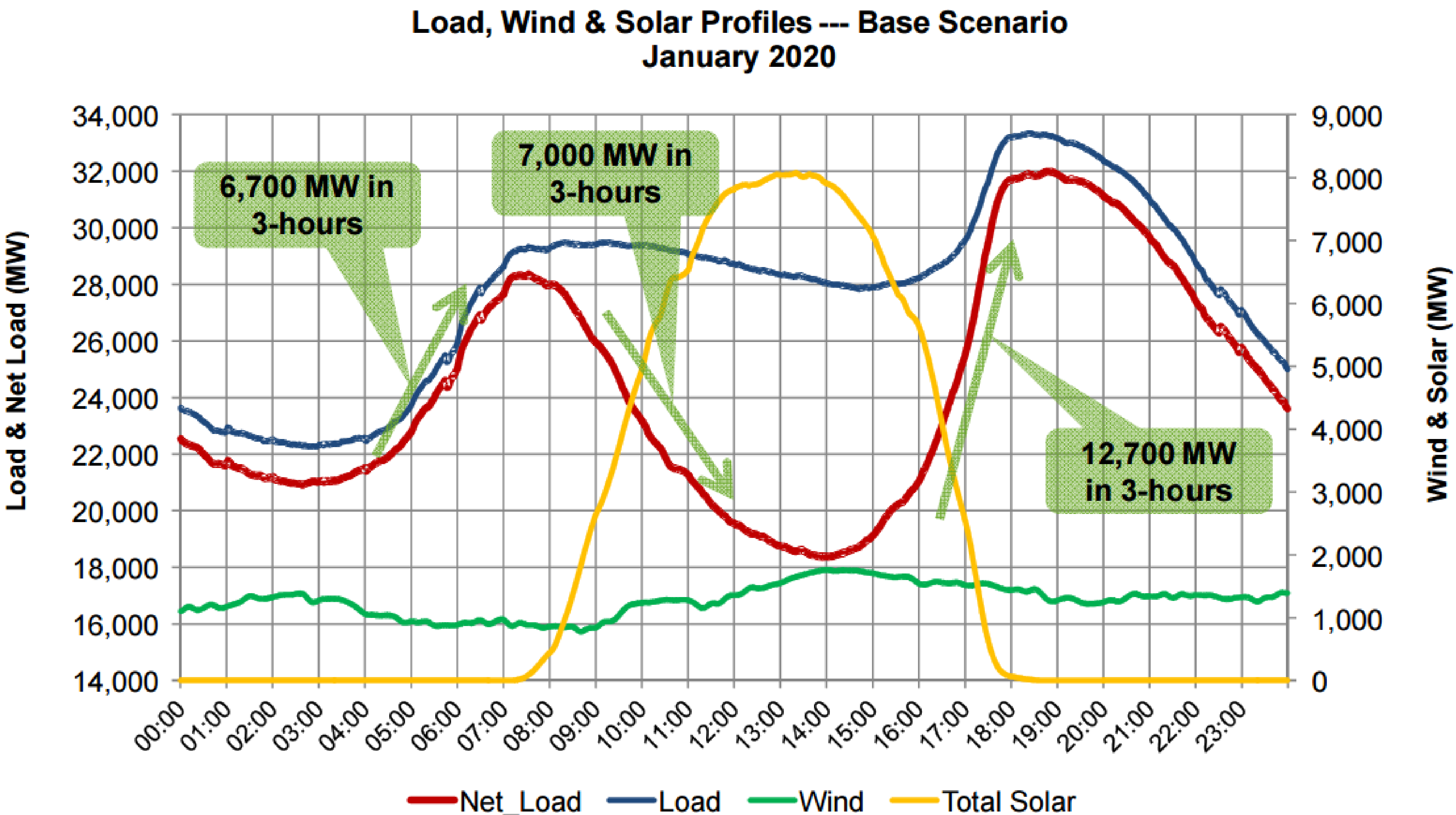
- High-speed energy injection following loss of resources
  - High-speed response during Arresting Phase of a Frequency Event
    - Response proportional to the change in frequency and rate of change in frequency
    - Help to offset loss of system inertia due to displacement or retirement of generation
- Continuous proportional response to frequency deviations
  - Frequency control services
- Energy injection to perform ramping services
  - Reduce severity of solar-based resource drop-off in evening

Potential Operating Mode for Battery Charging

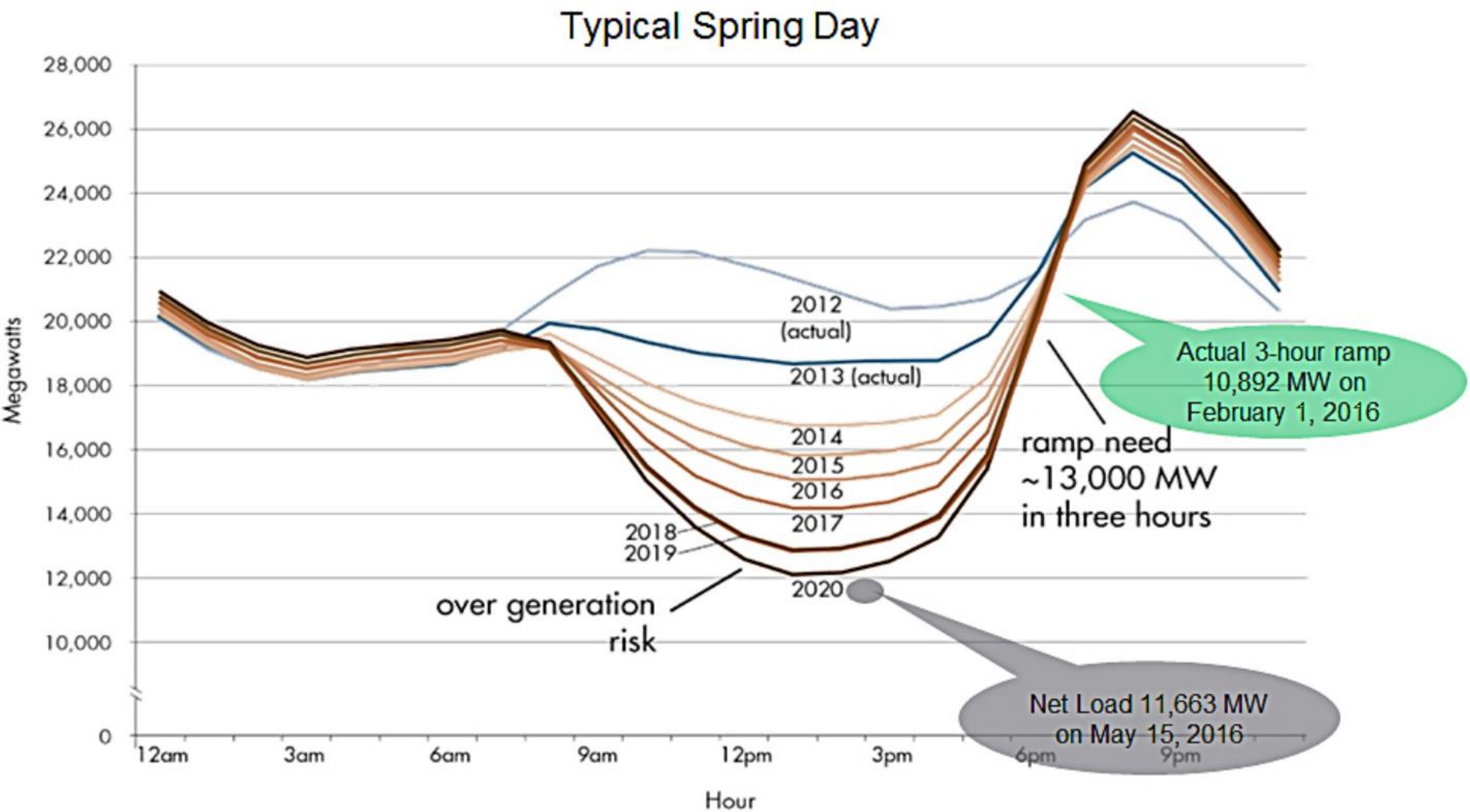


Energy storage can move from a charge to discharge cycle similar to traditional generator droop characteristic

CAISO Load Balancing Concerns

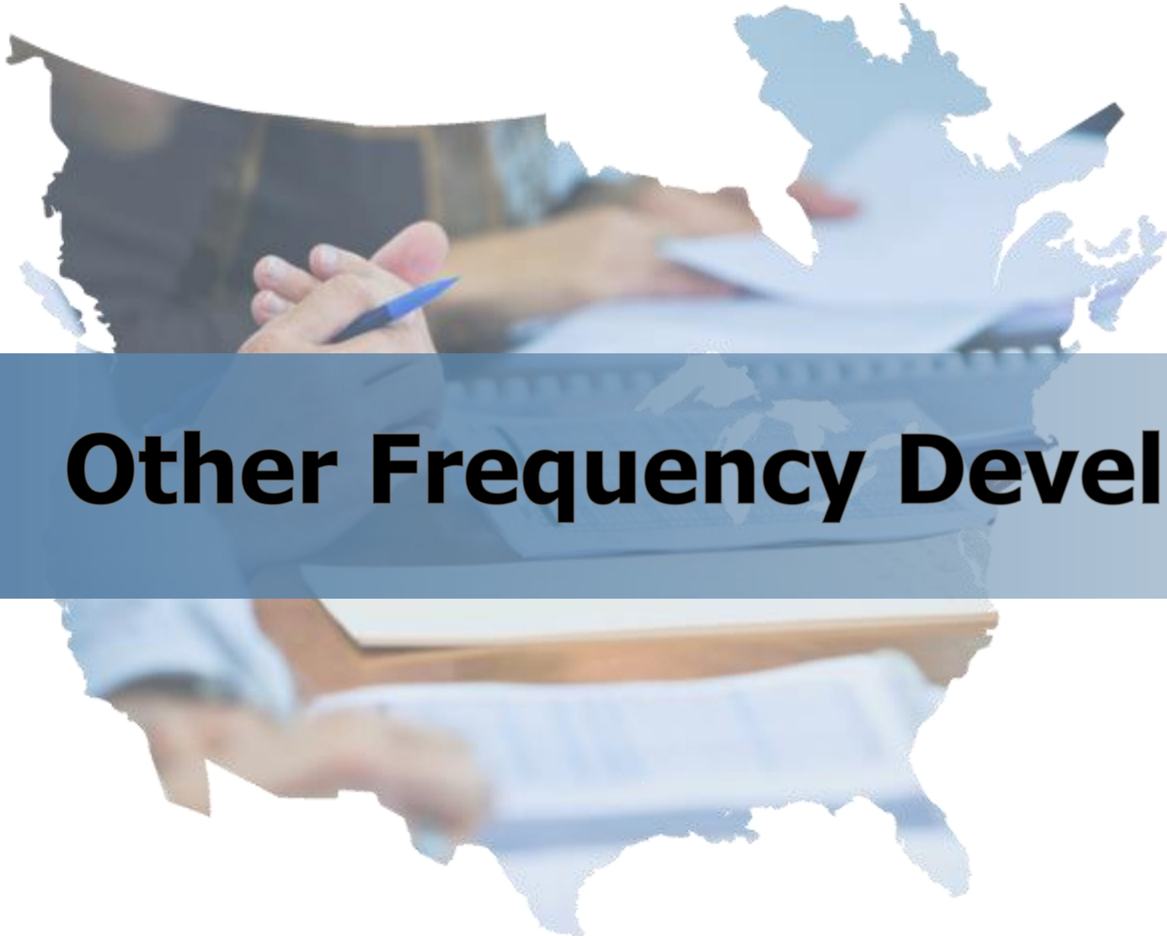


Updated Duck Curve – Exceeding Projections



Ramping / Load-Following Services Role for Storage

- Supplement generation during severe upward ramps
  - Morning load pick-up before solar reaches full output
  - Evening load pick-up when solar output is dropping off
- Absorb energy during downward ramps
  - When solar and wind output ramps up to full output and morning load stabilizes
- Absorb energy to prevent over-generation
  - Charge storage when solar and wind output exceeds energy demand
- Load-following to provide balance for variable resources
  - Wind and solar variability due to changes in weather



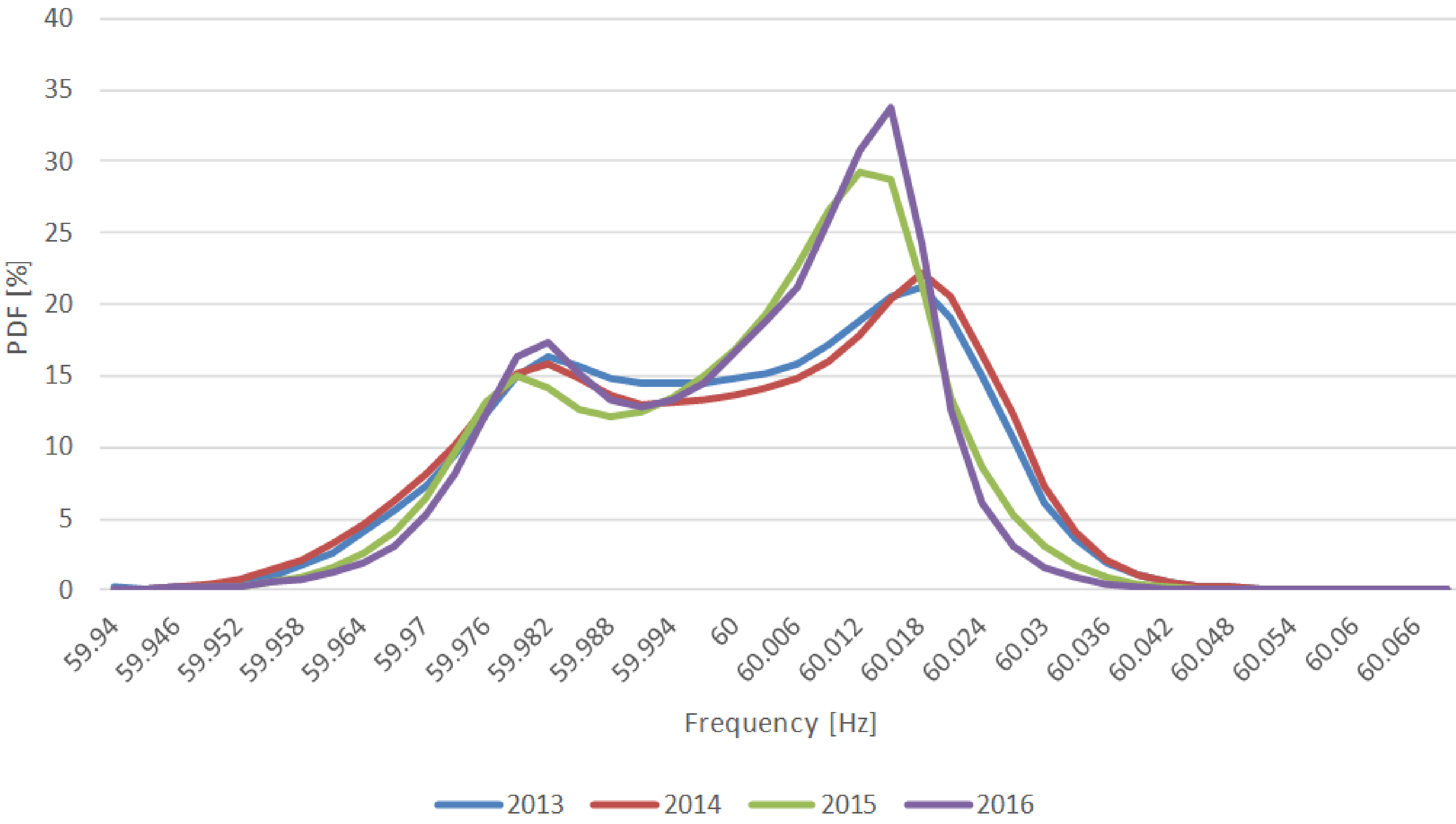
Other Frequency Developments

Other Frequency Developments

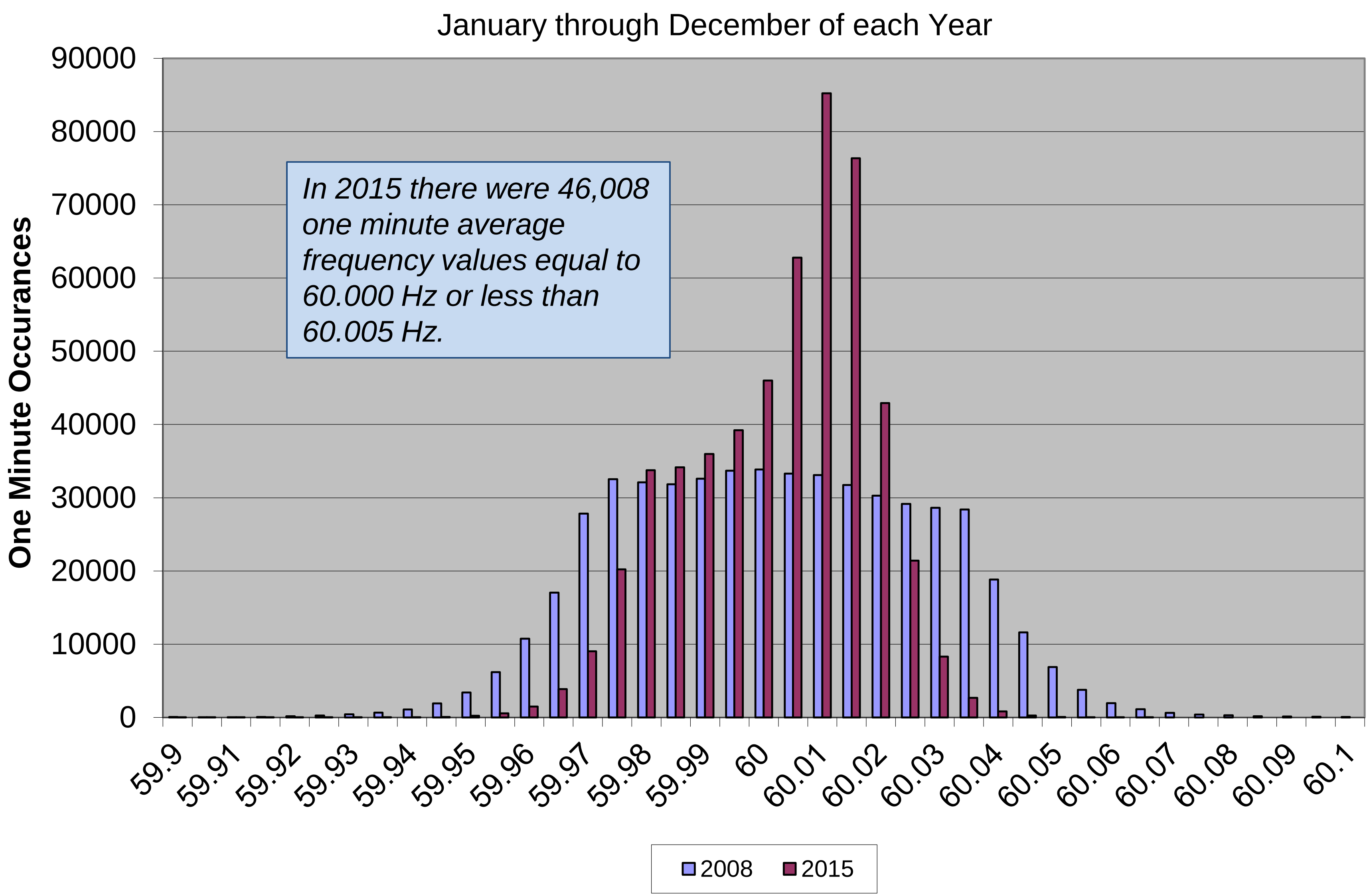
- Significant frequency characteristics changes in ERCOT
- TRE BAL-001 Standard in effect in 2015
  - Requires active frequency response on ALL resources, including wind
  - Sets deadband at ±0.0167 Hz

- Tremendous impact on frequency response and frequency characteristics

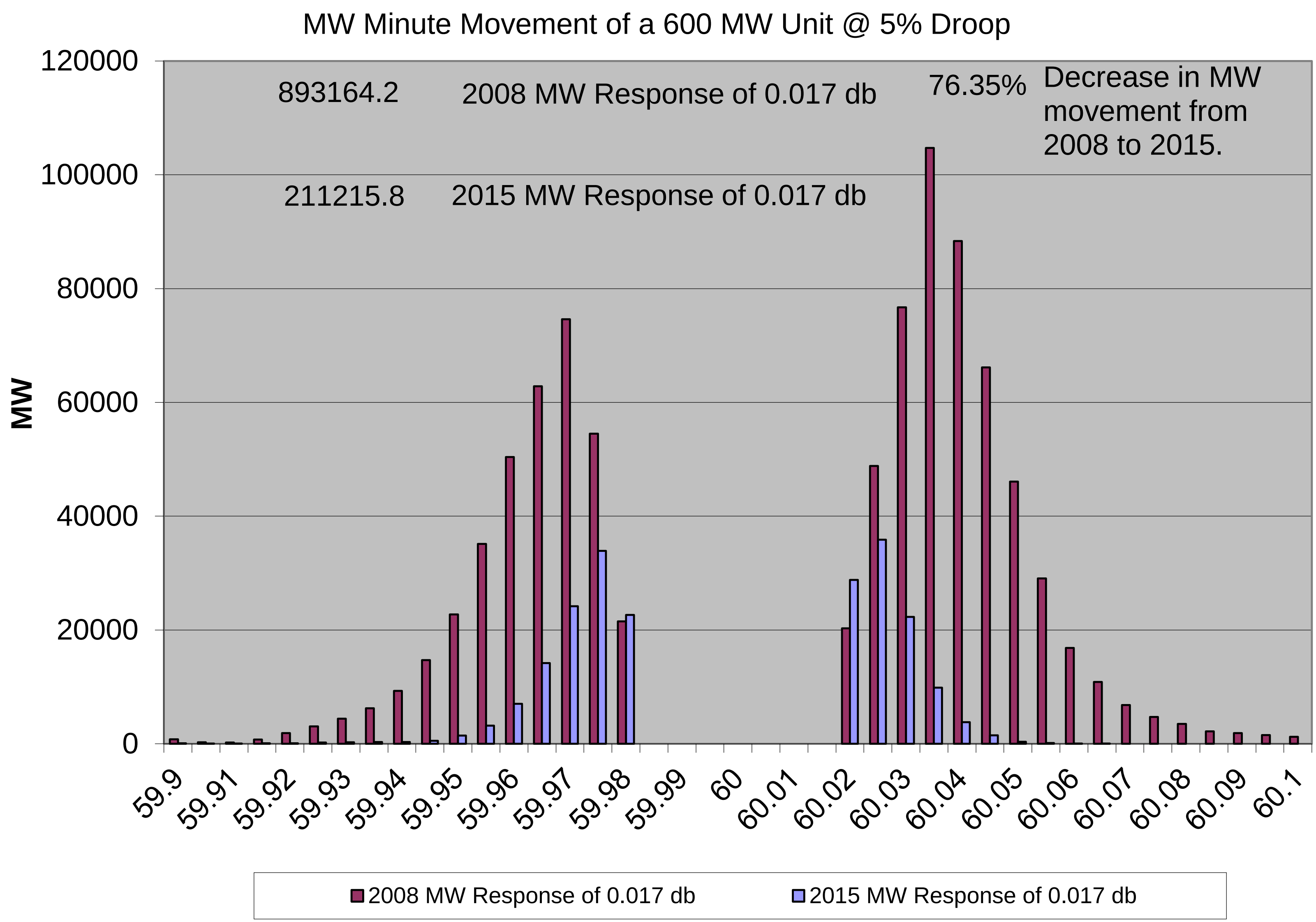
ERCOT Frequency Probability Density Analysis



ERCOT Frequency Profile Comparison



January thru December 2015 0.0166 db vs. 2008 0.0166 db



Questions and Answers