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Industry Webinar

White Paper: Fast Frequency Response Concepts and Bulk Power System Reliability Needs

April 16, 2020

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IRPTF White Paper


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Fast Frequency Response Concepts and Bulk Power System Reliability Needs

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

March 2020

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IRPTF Web Page Location

Inverter-Based Resource Performance Task Force

The purpose of the Inverter-Based Resource Performance Task Force (IRPTF) is to explore the performance characteristics of utility-scale inverter-based resources (e.g., solar photovoltaic (PV) and wind power resources) directly connected to the bulk power system (BPS). This task force will build off of the experience and lessons learned from the ad hoc task force created to investigate the loss of solar PV resources during the Blue Cut Fire event and other fault-induced solar PV resource loss events. The joint task force will address many of the recommendations from the Blue Cut Fire Disturbance Report, including additional system analysis, modeling, and review of inverter behavior under abnormal system conditions. Recommended performance characteristics will be developed along with other recommendations related to inverter-based resource performance, analysis, and modeling. The technical materials are intended to support the utility industry, Generator Owners with inverter-based resources, and equipment manufacturers by clearly articulating recommended performance characteristics, ensuring reliability through detailed system studies, and ensuring dynamic modeling capability and practices that support BPS reliability.

Summary of Activities: BPS-Connected Inverter-Based Resources and Distributed Energy Resources

Inverter-Based Resource Performance Task Force

Type	Title	Date
	IRPTF White Papers, Technical Reports, and Assessments (4)	
	Review of NERC Reliability Standards White Paper	3/16/2020
	Fast Frequency Response Concepts and BPS Reliability Needs White Paper	3/5/2020
	Inverter Based Resource Performance Task Force PRC-024-2 Gaps Whitepaper	2/7/2019
	Western Interconnection Resource Loss Protection Criteria Assessment	3/2/2018

https://www.nerc.com/comm/PC/Pages/Inverter-Based-Resource-Performance-Task-Force.aspx

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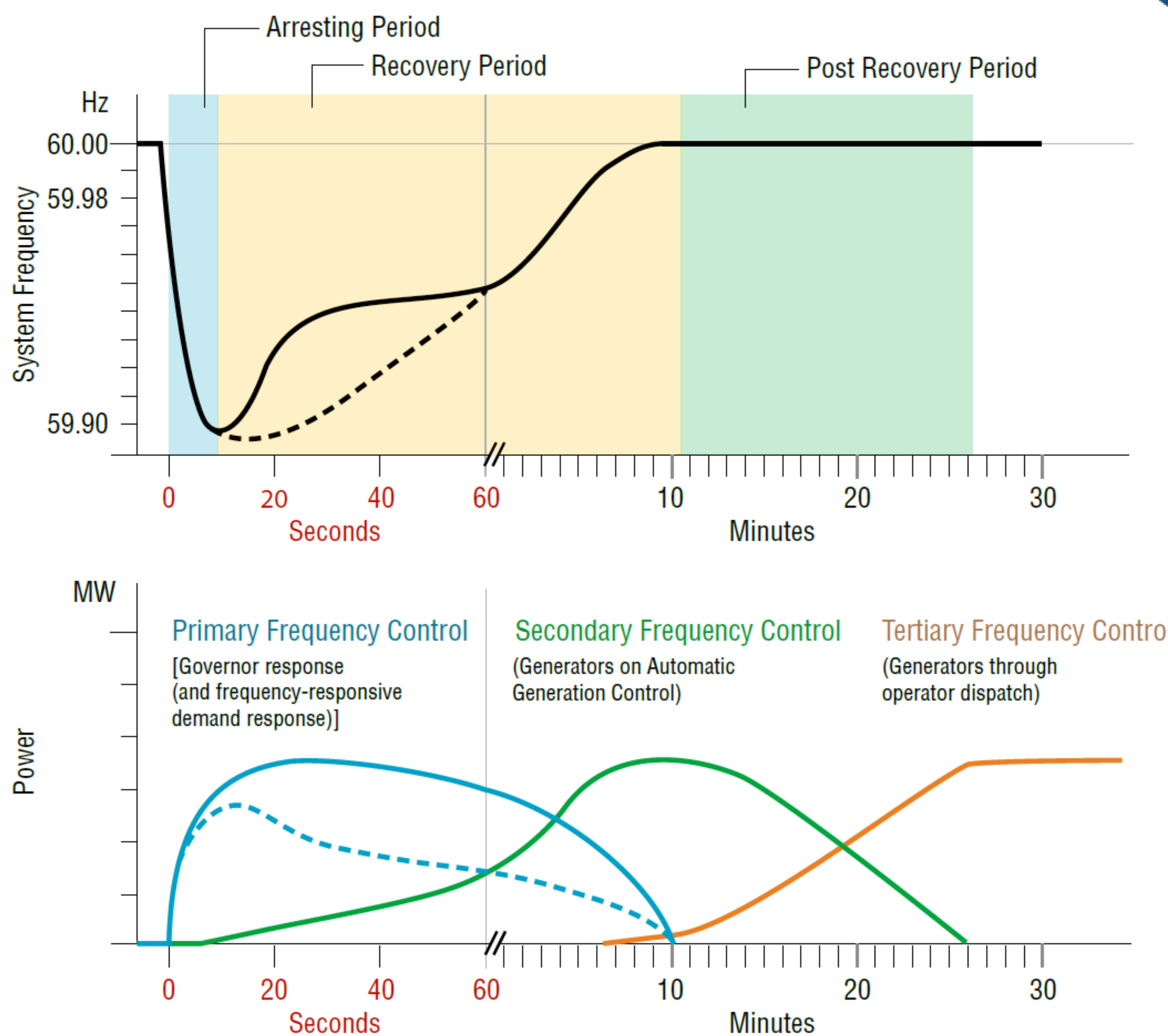
Overview of Webinar

Topic	Presenters
Frequency Response Fundamentals	Joe Eto, LBNL
Factors Affecting Fast Frequency Response	Ryan Quint, NERC
Fast Frequency Response Factors and Critical Inertia	Julia Matevosyan, ERCOT
Inverter-Based Fast Frequency Response Technology	Rajat Majumder, SGRE Sid Pant, GE
Application of Fast Frequency Response in ERCOT	Julia Matevosyan, ERCOT
Fast Frequency Response Around the World	Papiya Dattaray, EPRI
Wrap Up – Key Findings and Takeaways	Ryan Quint, NERC
Q&A	All

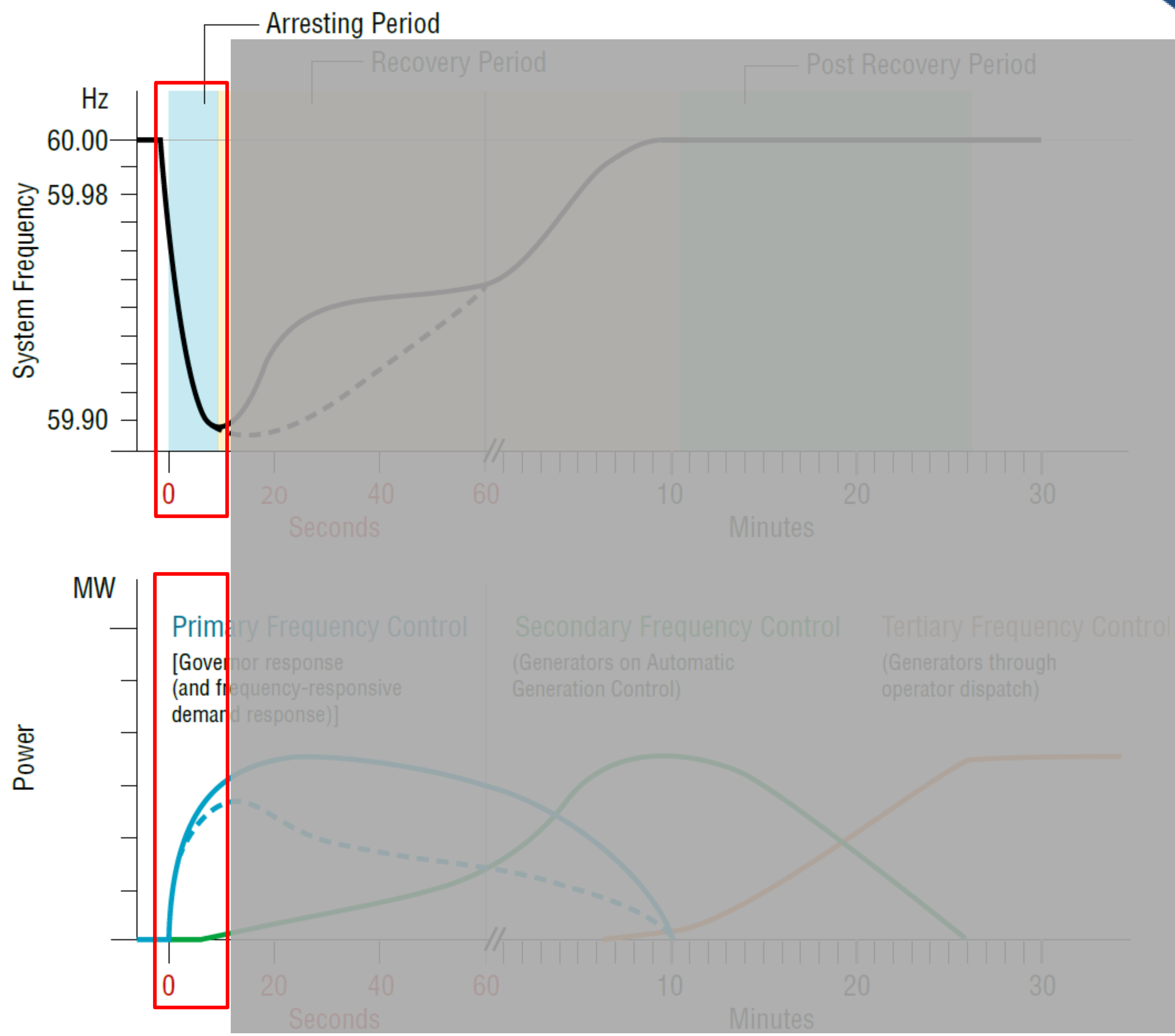
Frequency Response Fundamentals

Joe Eto, LBNL

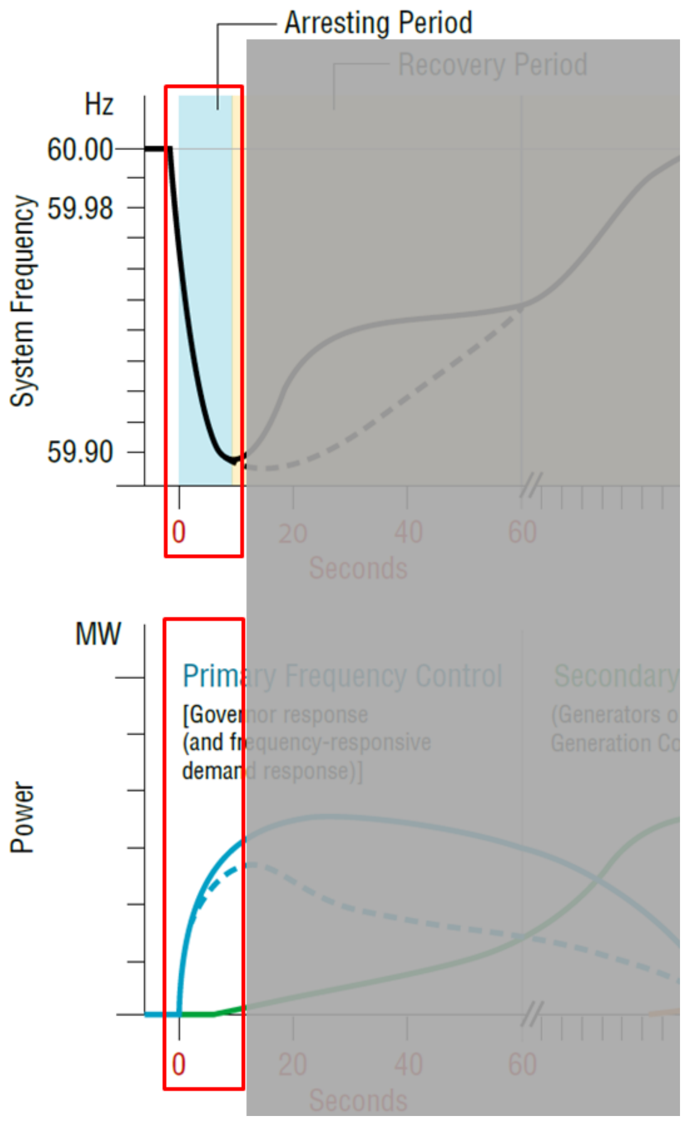
BPS Frequency Control Time Frames

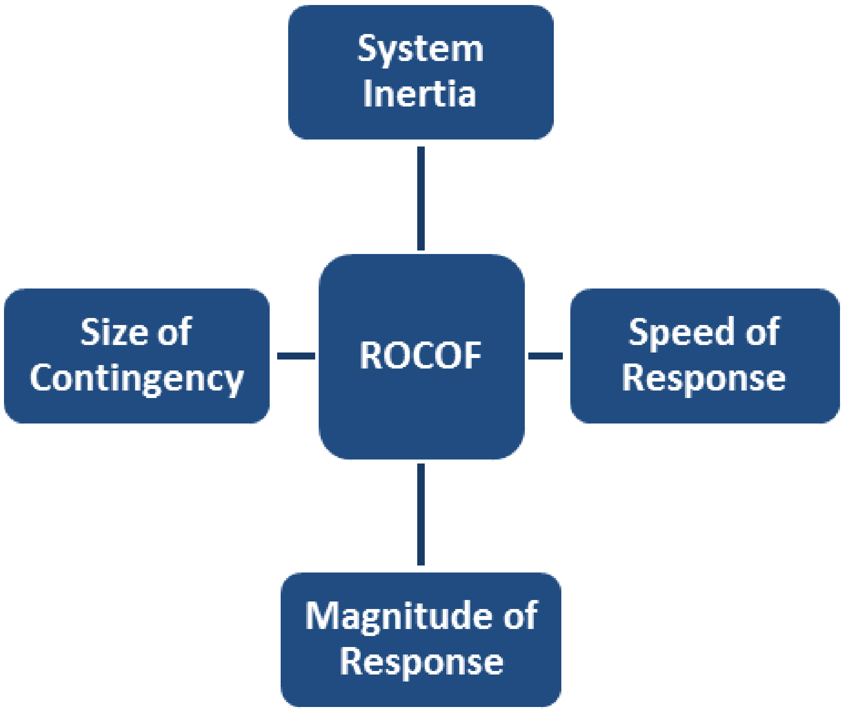


BPS Frequency Control Time Frames

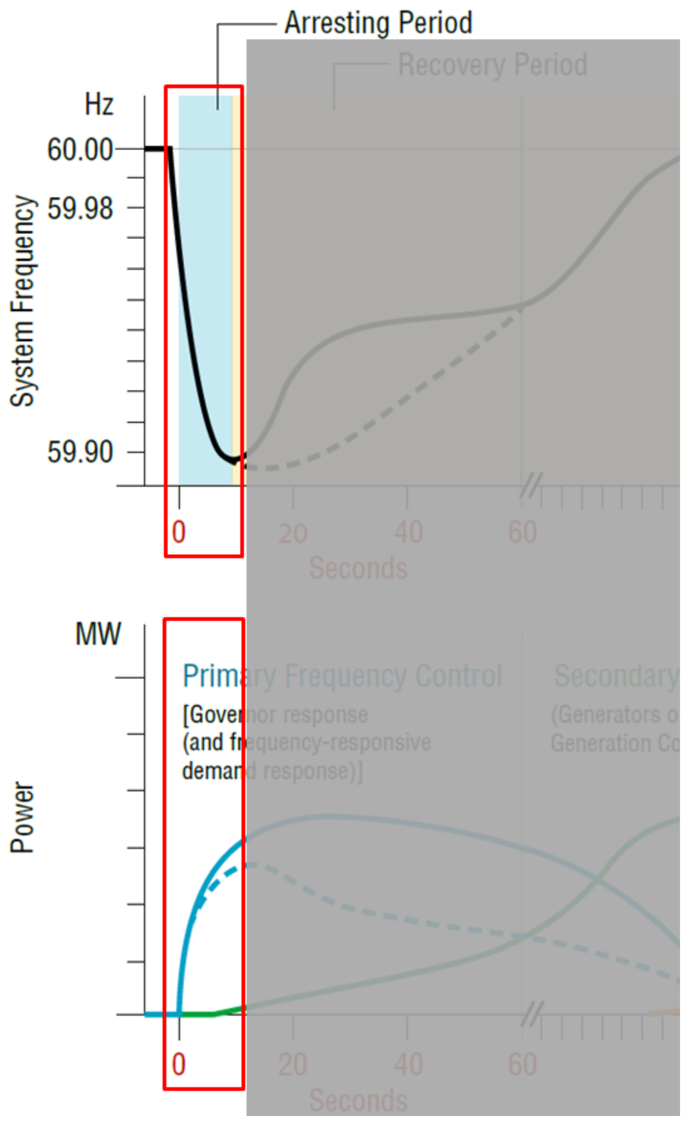


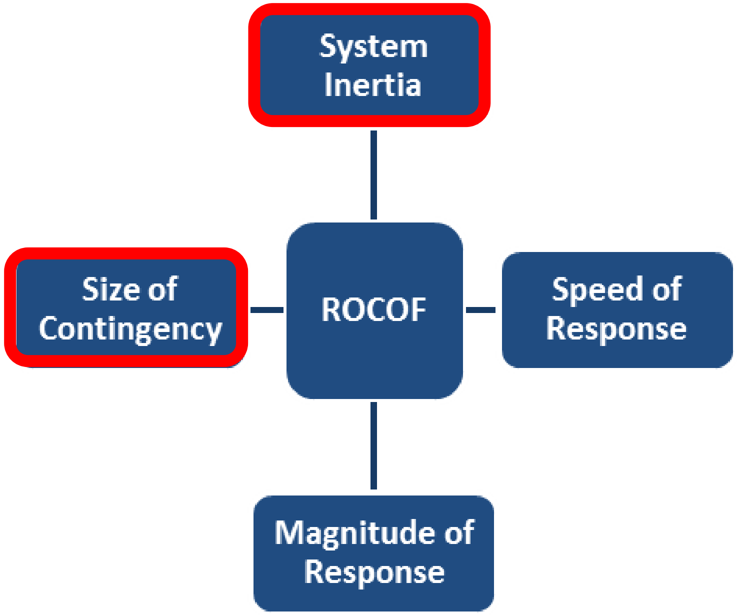
BPS Frequency Control Time Frames





BPS Frequency Control Time Frames





Design Criteria	Eastern Interconnection	Western Interconnection	Texas Interconnection
Largest Credible Contingency	4.5 GW	2.7 GW	2.7 GW
2015 Minimum Demand	210 GW	64 GW	24 GW
Contingency/Demand Ratio	2.1 %	4.1 %	11.3 %

Source: Developed by LBNL from NERC 2017 Frequency Response Annual Analysis (2017) and J. Matevosyan Inertia Data (2016).

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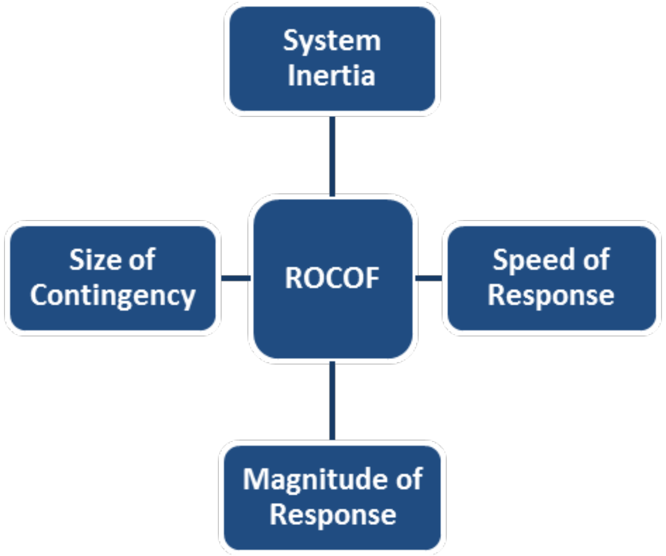
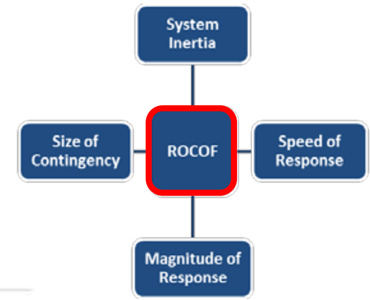
Factors Affecting Frequency Response

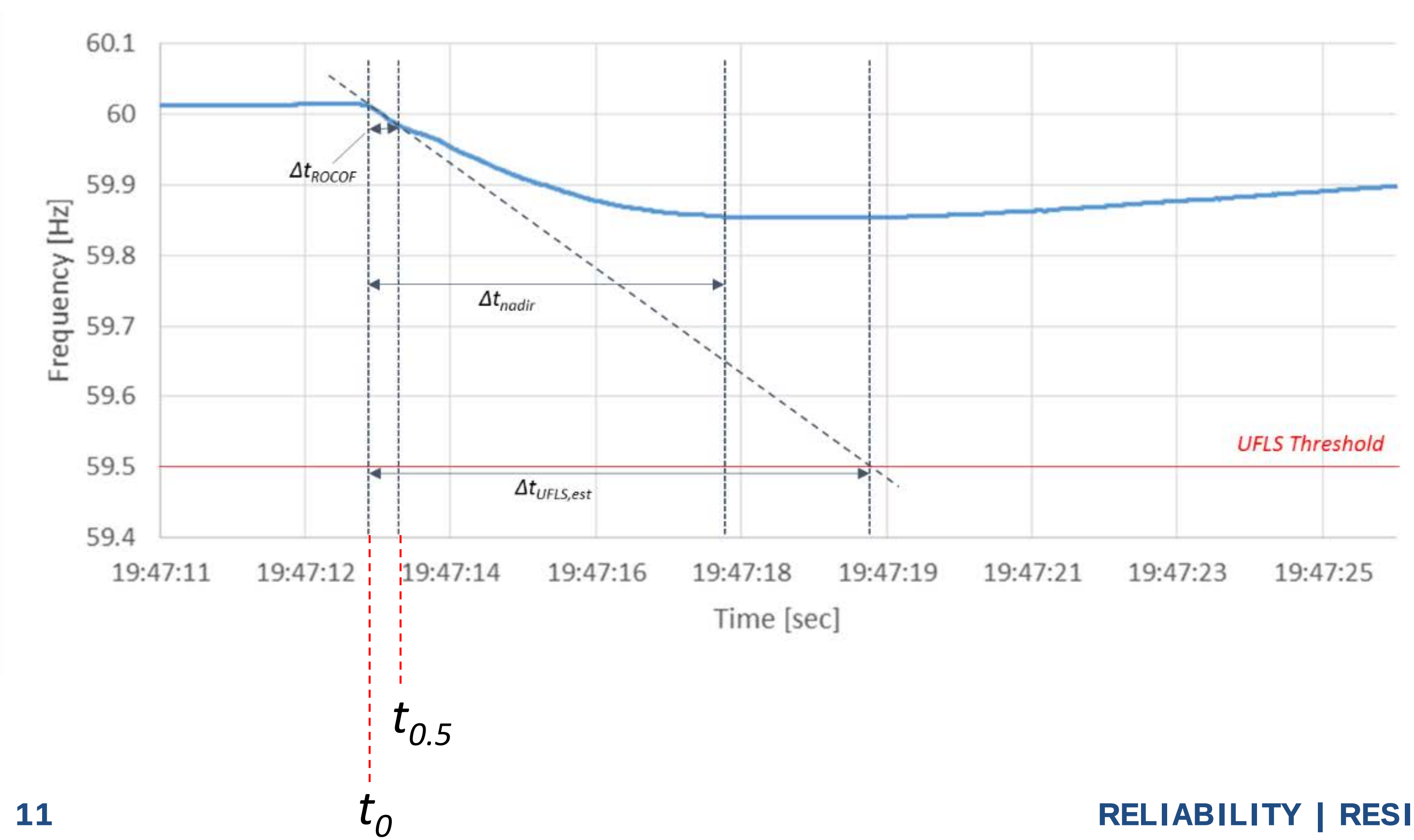
Ryan Quint, NERC



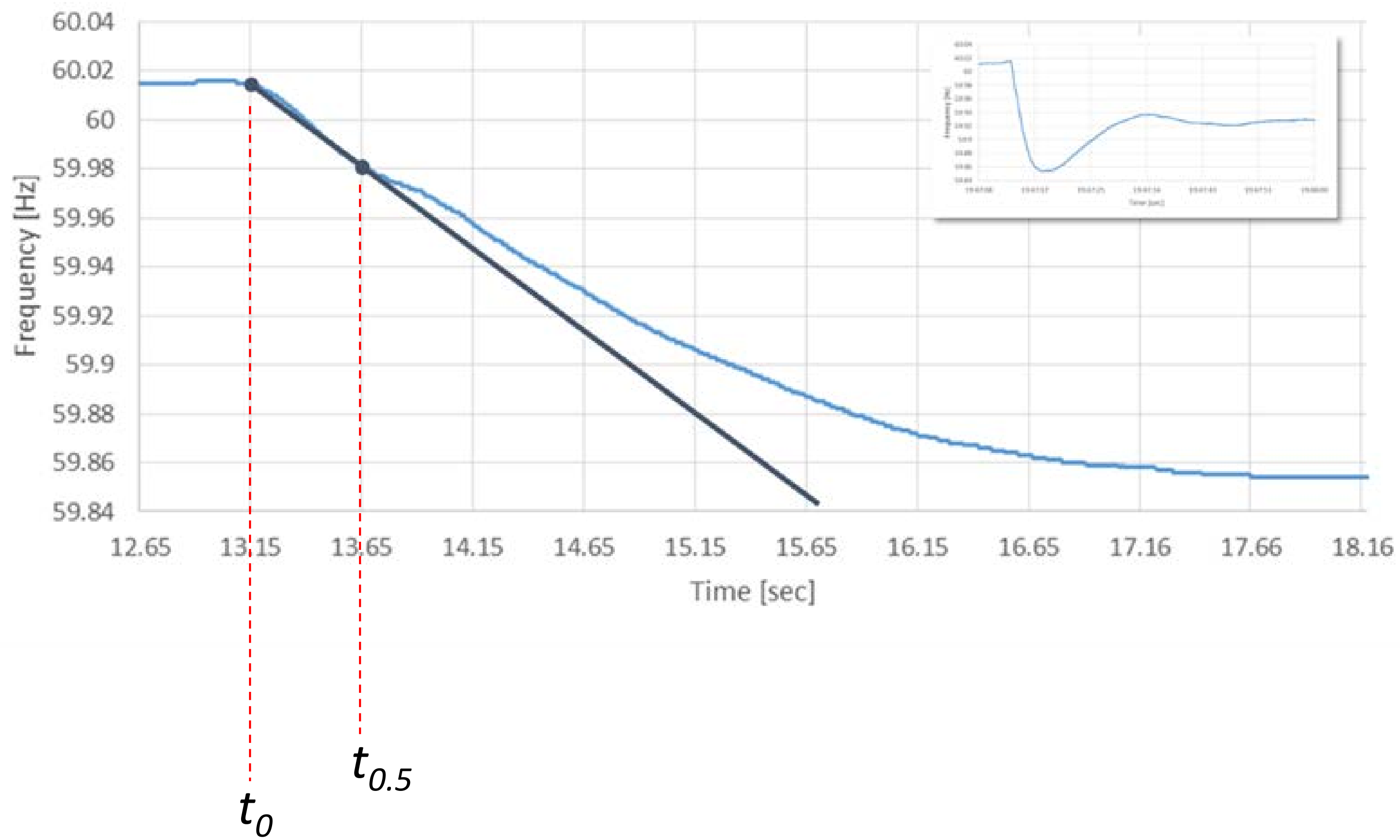
Calculating ROCOF



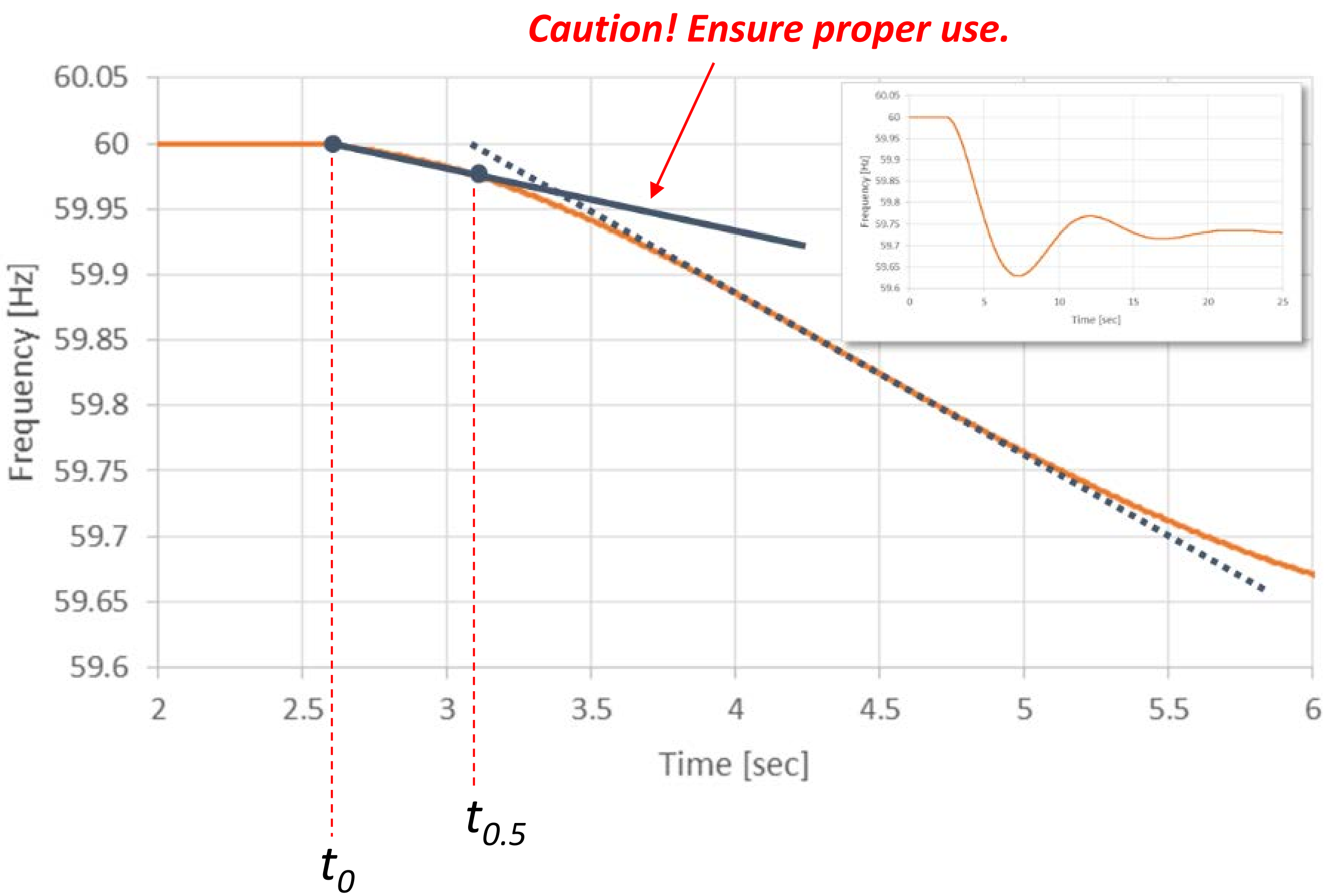
$$ROCOF_{0.5} = \frac{f_{0.5} - f_0}{0.5s}$$



ROCOF Example: Texas Interconnection



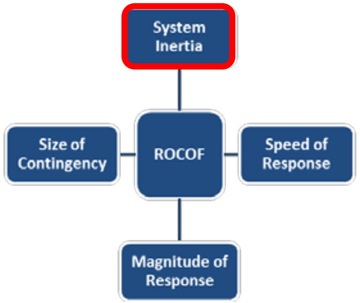
ROCOF Example: Western Interconnection



System Inertia

- Power system synchronous inertia:

  "the ability of a power system to oppose changes in system frequency due to resistance provided by rotating masses"

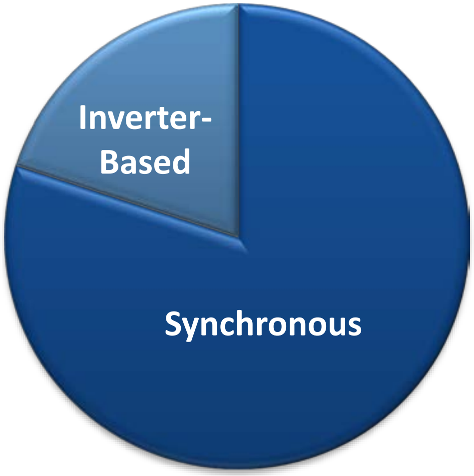


- Summation of kinetic energy stored in rotating masses of synchronously connected machines
  - Synchronous generators, synchronous condensers, synchronous motor loads

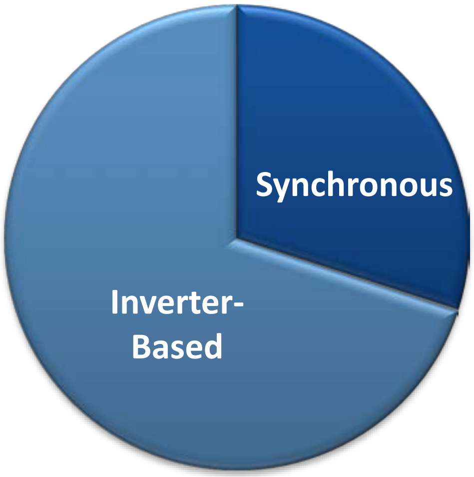
$$KE_{sys} = \sum_{i \in I} H_i * MVA_i$$

- When a sudden change in gen or load occurs, synchronous machines and the electric system inherently exchange kinetic energy → machines change speed (i.e., "inertial response")

System Inertia

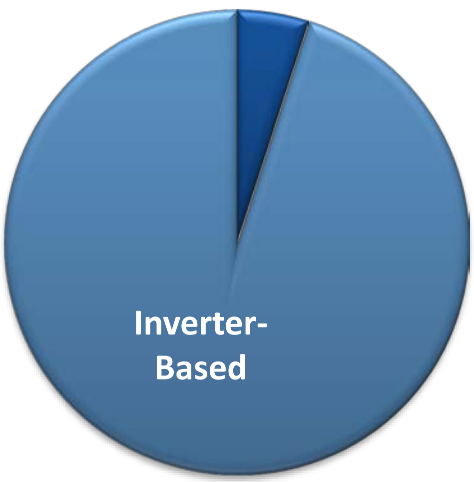


- Historically…
  - Synchronous generator-based system
  - Lower instantaneous penetrations of inverter-based resources
  - Higher synchronous inertia, lower ROCOF
  - Sufficient time for primary frequency response to deploy and UFLS to operate

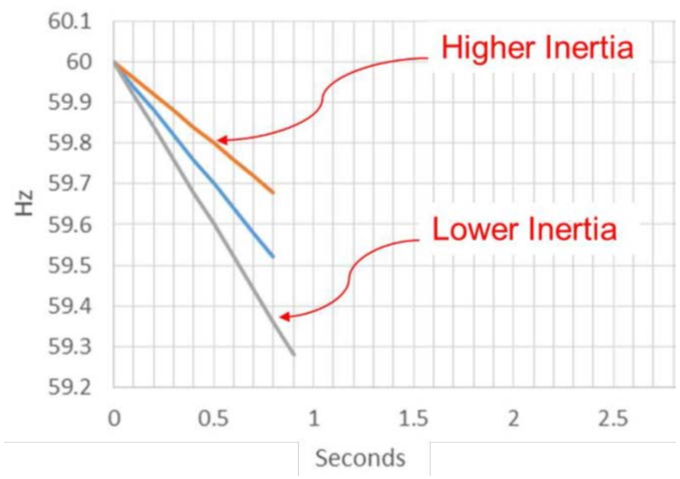


- Today…
  - Mixed synchronous and inverter-based system
  - Increasing instantaneous penetrations of inverter-based resources (some not responsive to frequency changes
  - Decreasing synchronous inertia, rising ROCOF
  - Likelihood of shorter time for primary frequency response to deploy and UFLS to operate

System Inertia

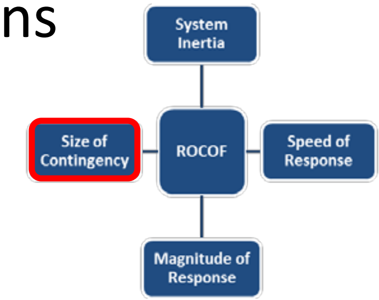


- Future…
  - Predominantly inverter-based system (in some areas)
  - Very high **instantaneous** penetrations of inverter-based resources (may or may not respond to under-frequency conditions)
  - Very low synchronous inertia, very high ROCOF
  - Challenges with delivering primary frequency response, need for faster controls
  - Challenges with ensuring coordinated operation of UFLS

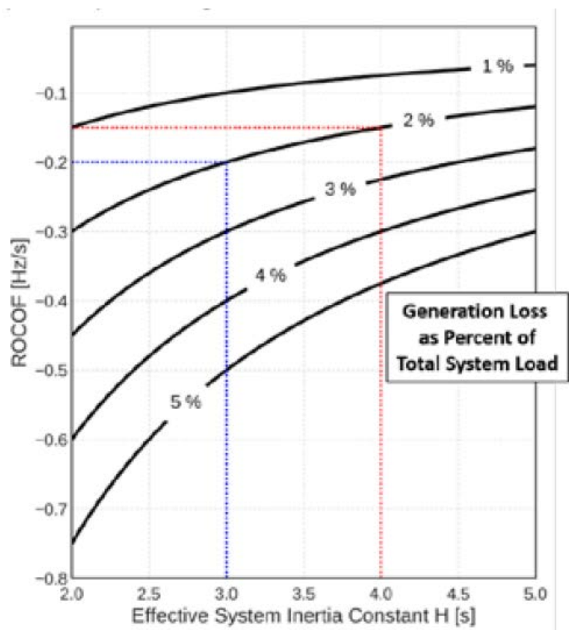


- As system inertia reduces, ROCOF gets higher (steeper) with all other factors held constant

Size of Largest Credible Contingency



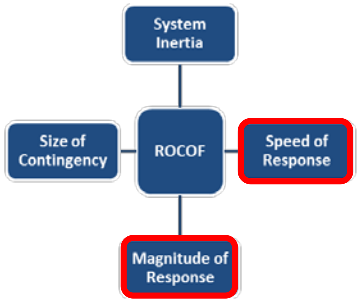
- As BPS experiences higher instantaneous penetrations of inverter-based resources, system inertia may decrease
  - As system inertia decreases, ROCOF increases nonlinearly
  - Size of the largest credible contingency also affects the ROCOF
  - Size of largest credible contingency may change over time

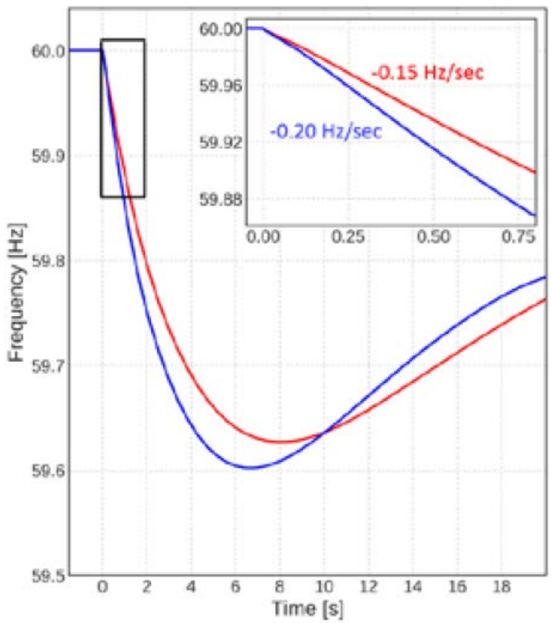


- Example 1 (red):
  - System inertia constant (H) = 4.0
  - Contingency size is 2%
  - So, ROCOF is -0.15 Hz/sec
- Example 2 (blue):
  - System inertia constant (H) = 3.0
  - Contingency size is still 2%
  - So, ROCOF is -0.20 Hz/sec

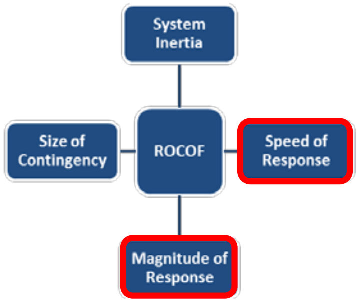
Speed and Magnitude of Response

- Energy injected before the frequency nadir improves the frequency deviation
- Ideal frequency response from units has very little to no time delay
  - "Lazy L" shaped, where frequency falls to level determined by effective droop of the system
- However, many resources take longer to deliver additional power in response to changing frequency, and their response continues after frequency nadir reached
  - This drives rebounding of frequency in some Interconnections (e.g., Texas, Western, Quebec)

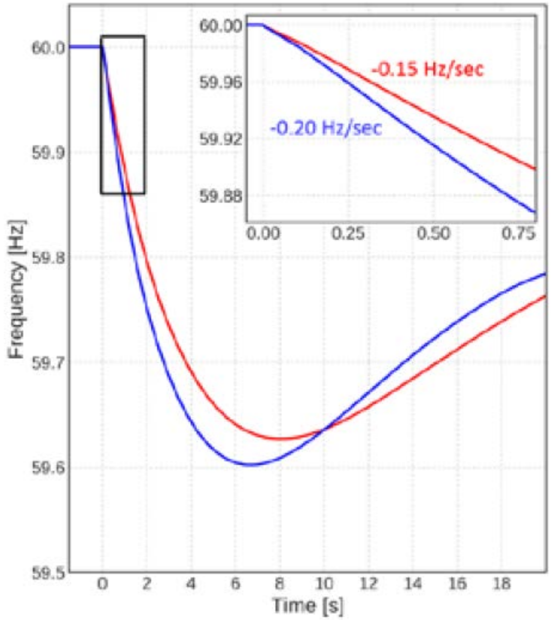




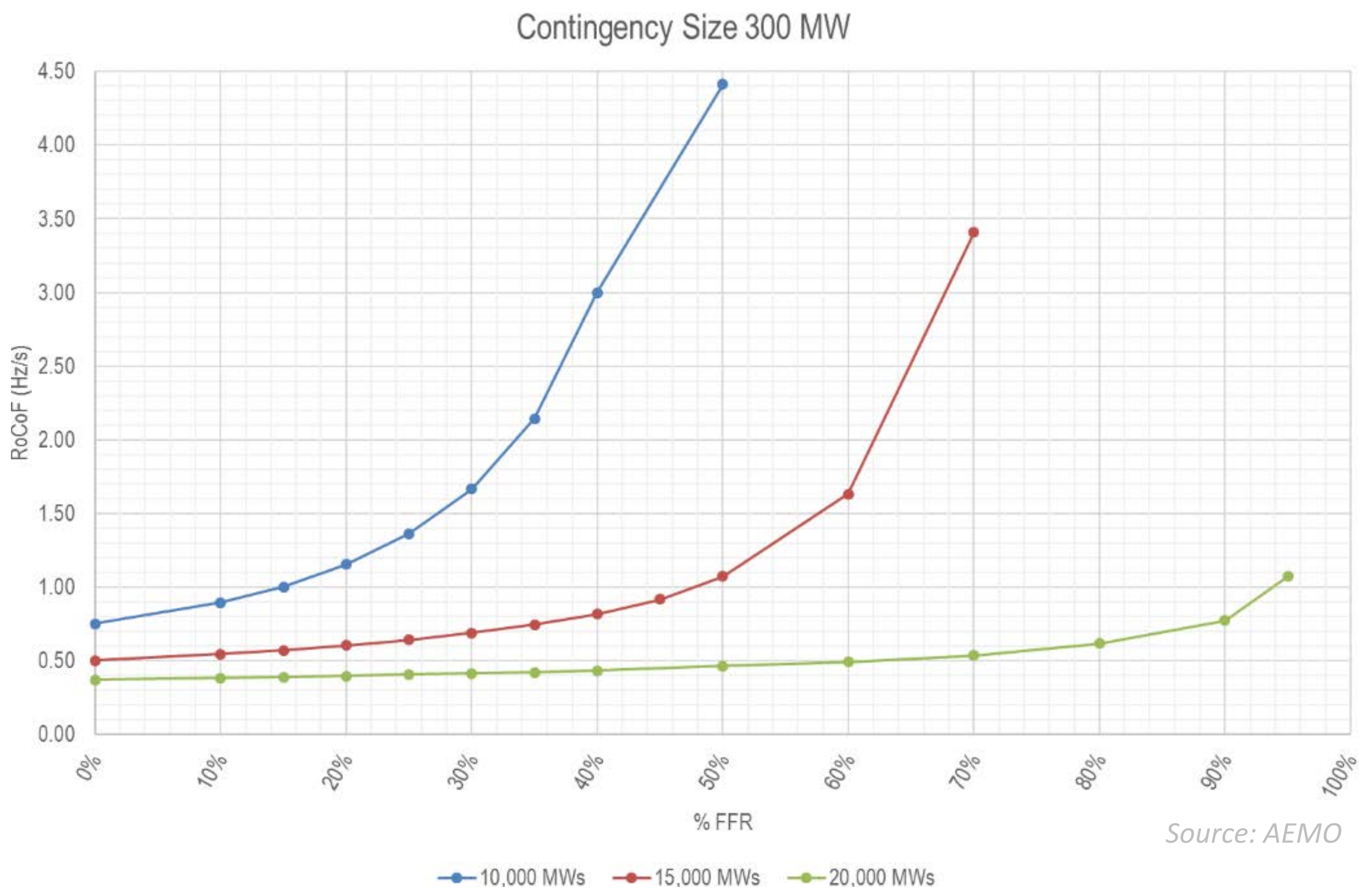
Speed and Magnitude of Response



- As instantaneous penetration of inverter-based resources increases, system ROCOF will increase; time available to deliver frequency responsive reserves will shorten
  - Due to reduction of synchronous resources previously providing inertia
  - Drives need for faster-acting frequency responsive resources to inject (or in the case of load resources, to withdraw) energy to the grid during a shorter arresting period
- Speed of response (and ability to provide FFR) may be limited by technology
- Magnitude is dependent on speed of response and droop characteristic



ROCOF versus % FFR



Source: AEMO

Other Factors

- Generator Dispatch
  - Affects amount of committed resources to meet demand and carry sufficient amounts of ERSs (including frequency responsive reserves)
    - Start-up and shut-down times and costs, ramp rates, outage schedules, energy certainty, etc.
  - Example:
    - High inverter-based resource condition assumed to be a "low inertia";
    - However, possible that during these conditions a significant amount of on-line synchronous generation providing ERSs (and scheduled to provide higher power output in subsequent hours) will increase the system inertia at that time
- Load Frequency Sensitivity
  - Frequency-sensitive loads may result in demand reduction during arresting phase (e.g., motor loads)
  - Frequency sensitivity historically assumed to be around 1–1.5%
  - Power electronic loads may not exhibit this sensitivity

Fast Frequency Response Factors and Critical Inertia

Julia Matevosyan, ERCOT

Definition of Frequency Response

- **Fast Frequency Response:** power injected to (or absorbed from) the grid in response to changes in measured or observed frequency* during the arresting phase of a frequency excursion event to improve the frequency nadir or initial rate-of-change of frequency

*In many cases, this is a response to locally measured frequency (or other local signal). In some cases, where speed of response is critical, other types of signals may be used to initiate FFR. For example, RAS actions triggered by specific contingencies may activate FFR.

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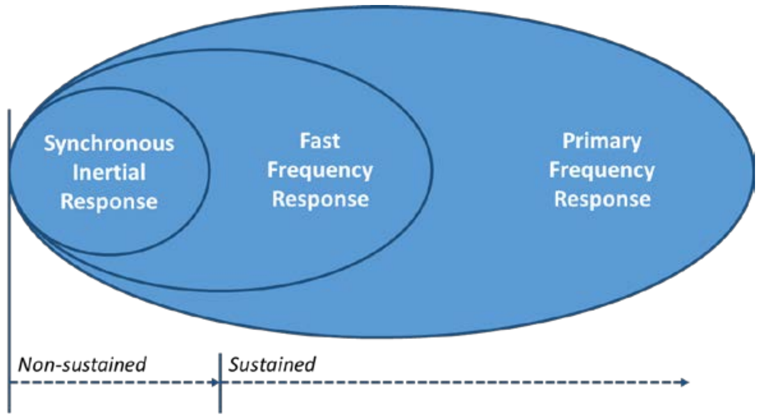
Fundamental Aspects of FFR

- Overall system frequency response should be sustained*
  - Arrest frequency excursions, maintain frequency stability, and adequately allow frequency recovery

    *A characteristic of frequency response in requirements set forth in FERC Order No. 842

- Different technologies provide FFR in different ways
  - Some may be sustained, others may not
  - Each helps arrest frequency change, improve frequency nadir
  - Should be coordinated with PFR to support frequency control



Fundamental Aspects of FFR

- Large synchronous inertia → low initial ROCOF → minimal need to distinguish between PFR and FFR
  - Sufficient time for synchronous inertial response and conventional active power-frequency controls (e.g., turbine-governors)
  - Little need for additional requirements, services, or controls

- "*Fast*" (in *F*FR) is relative to arresting period
  - Differs across interconnections
  - Driven by reliability need, not arbitrary
  - Should not be generalized

Fundamental Aspects of FFR

- Like PFR, FFR can involve small changes in active power output from generating resources
  - FFR should not degrade stability of generating resource
    - Faster response may not always be desirable (e.g., areas of low short-circuit strength)
  - Closed-loop FFR control with fast time constants will deliver energy to the grid based on the grid needs

- FFR used in inverter-based resources should be tuned appropriately
  - Large voltage perturbations → coordinate FFR with other competing inverter controls, particularly when the inverter is current-limited
  - Control action should be based on an appropriate calculation of frequency (often requires time delay)

Fundamental Aspects of FFR

- Currently no requirements for resources to maintain frequency responsive reserve, or "headroom"
  - Headroom needed to respond to underfrequency events

- Responsibility of BA to ensure adequate amounts of frequency responsive reserves available to arrest frequency decline and avoid UFLS operation for largest credible contingency
  - Includes consideration of sufficiently fast response
  - Some inverter-based resources may have contractual limits less than total nameplate rating of individual generating units
  - Excess capacity could be used for FFR or PFR, if allowed by BA

Fundamental Aspects of FFR

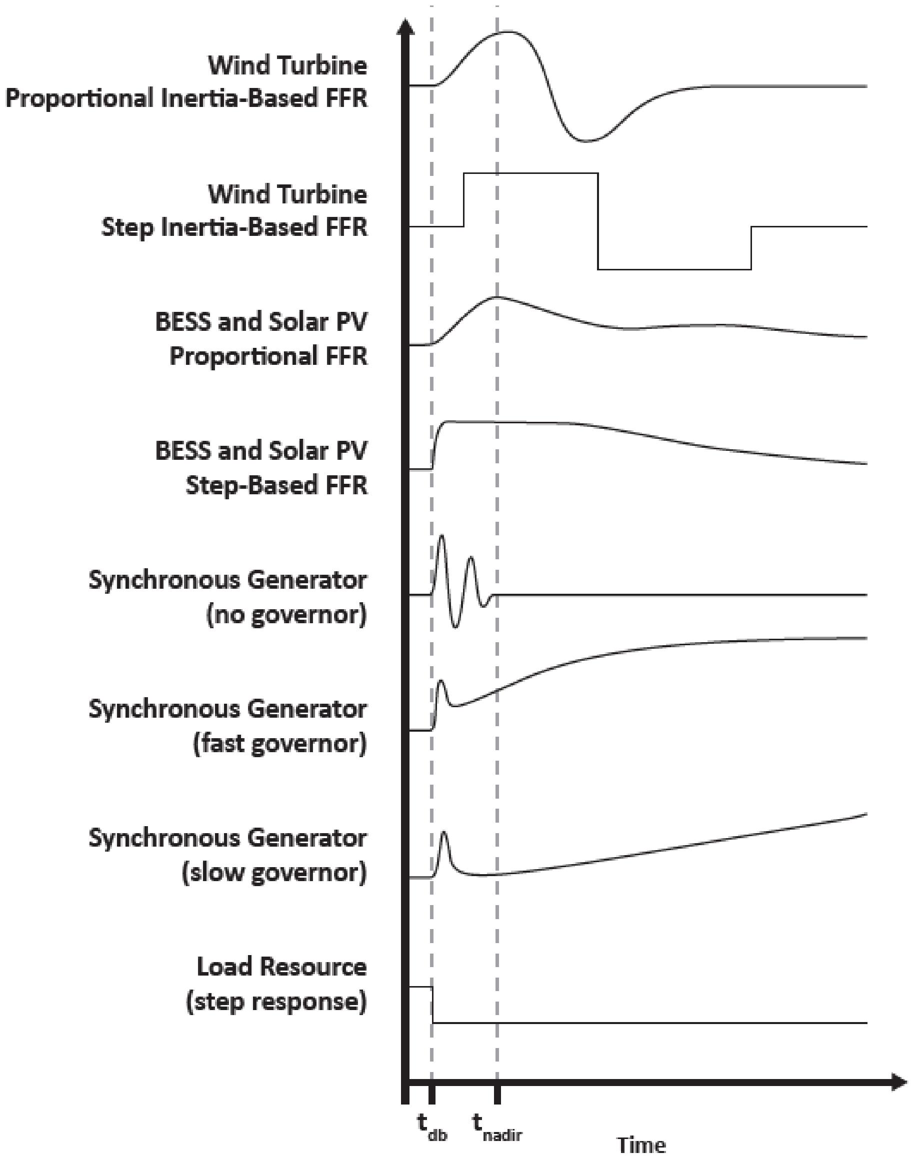
- Present technology of BPS-connected inverter-based resources have capability to provide FFR, given equipment limitations
  - Capability of providing FFR should be designed and configurable (field adjustable) in all BPS-connected inverter-based resources
  - Actual settings for installed equipment may vary based on grid needs

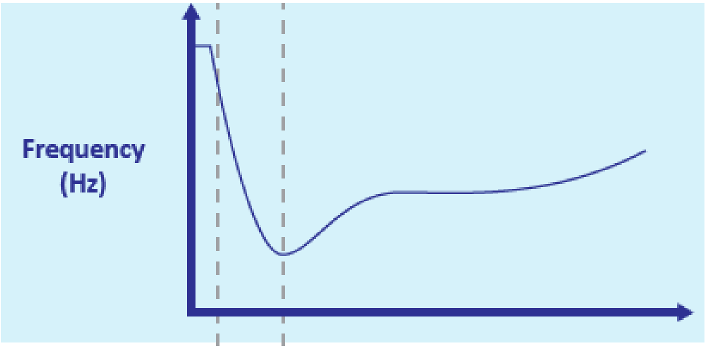
- Non-sustained FFR should not negatively impact overall frequency response or frequency control

Types of FFR

- Activation of FFR can take different forms, including any one or combination of the following:
  - Active power injection in proportion to measured frequency deviation or ROCOF
    - Proportional or derivative response
  - Injection of constant amount of active power once frequency reaches a preset frequency or ROCOF trigger
    - Step response
  - Controlled load reduction in proportion to measured frequency deviation or ROCOF
    - Proportional or derivative response
  - Controlled reduction of constant amount of load on a preset frequency or ROCOF is reached
    - Step response

Illustration of Types of FFR



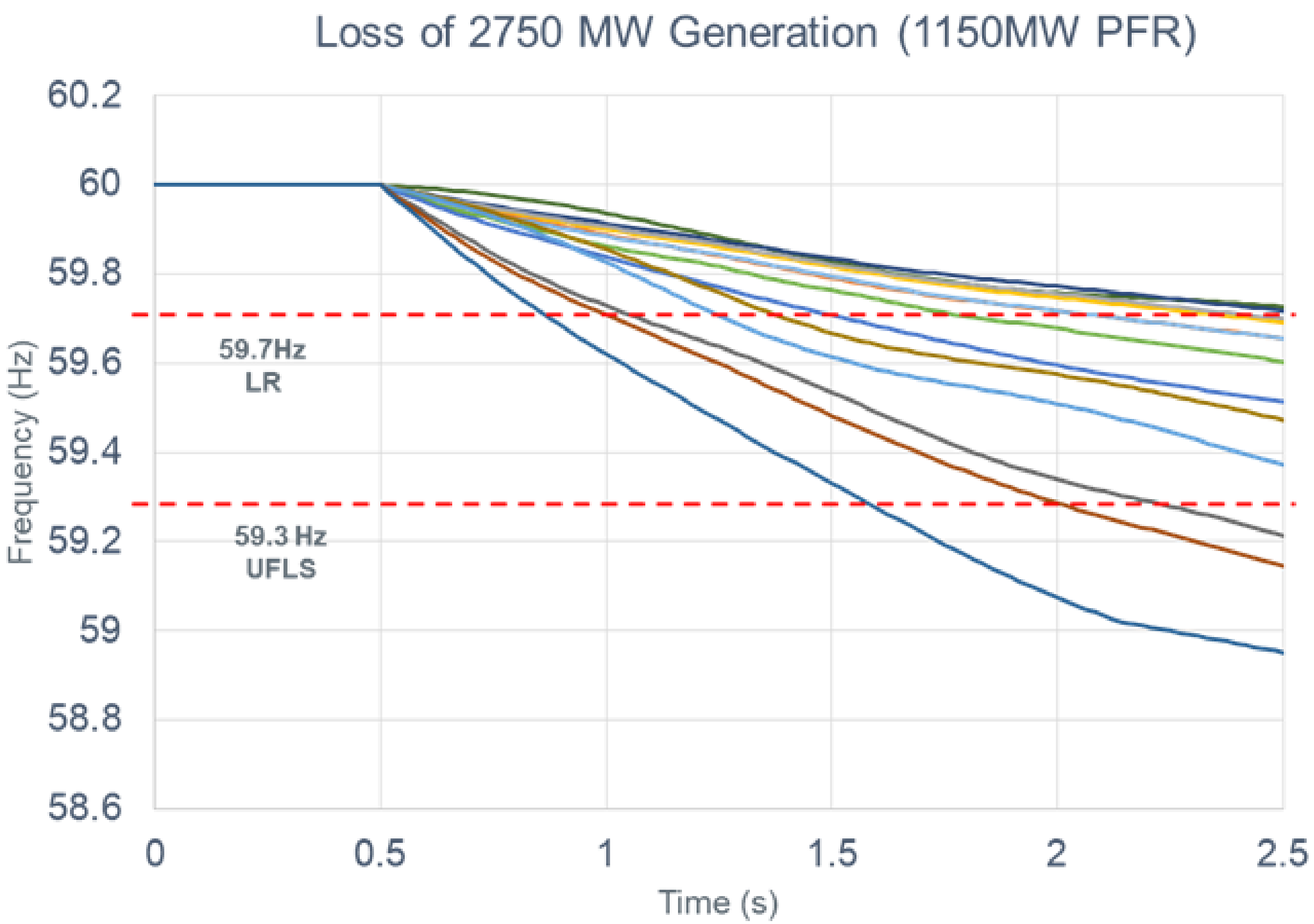


Critical Inertia

- **Critical Inertia:** the minimum level of system inertia necessary to ensure that frequency responsive reserves (both FFR and PFR) have sufficient time to be deployed and prevent the operation of the first stage of UFLS after the largest credible contingency.*

*Generally, the largest credible contingency is referred to as the Resource Loss Protection Criteria in BAL-003.

ERCOT Critical Inertia Studies

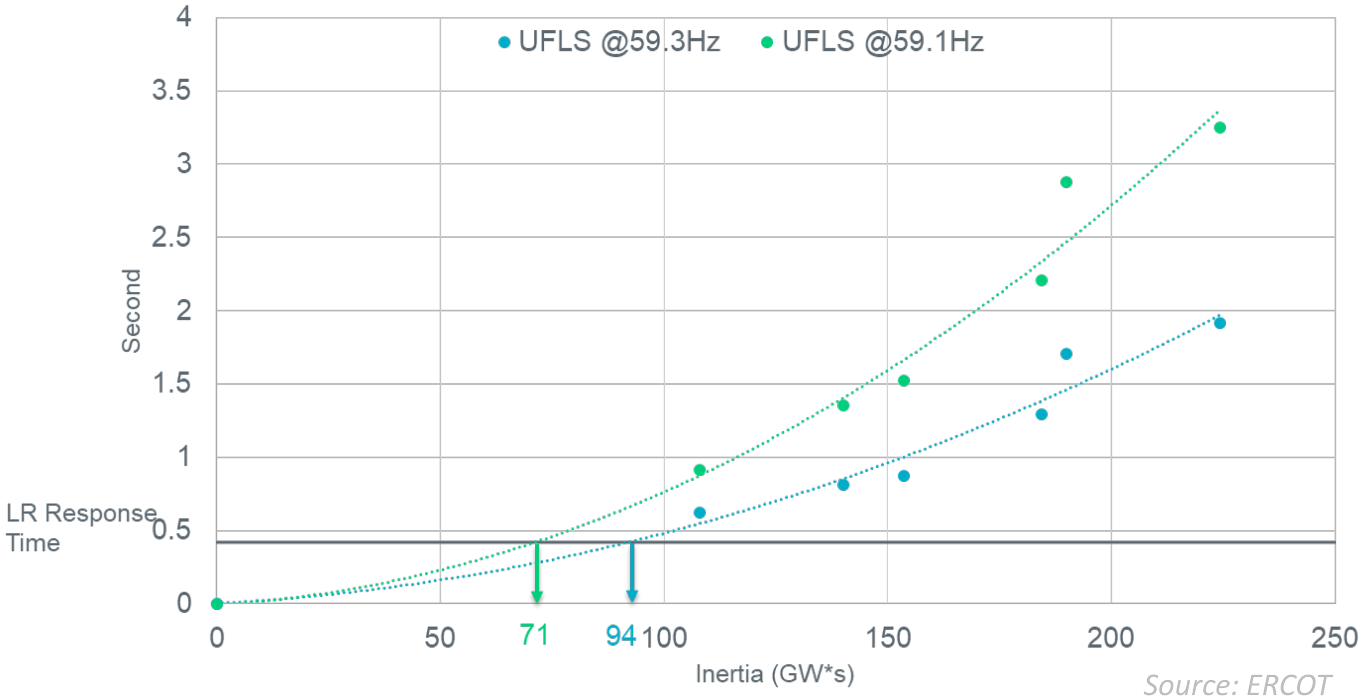


	Inertia (GW.s)
case13	376
case12	358.5
case11	340
case10	324
case9	307
case8	290
case7	260
case6	224.3
case5	190
case4	184.3
case3	153.6
case2	140
case1	108

Source: ERCOT

Critical Inertia Factors

- Critical inertia can be lowered by:
  - Introducing faster and/or “earlier” frequency response
  - Lowering UFLS setting
  - Reducing size of the largest contingency



Source: ERCOT

Inverter-Based Resource
Fast Frequency Response Technology

Rajat Majumder, SGRE

Sid Pant, GE

Inertia-Based FFR from WTGs

$$Power_{WTG} = Torque_{WTG} * Speed_{WTG}$$

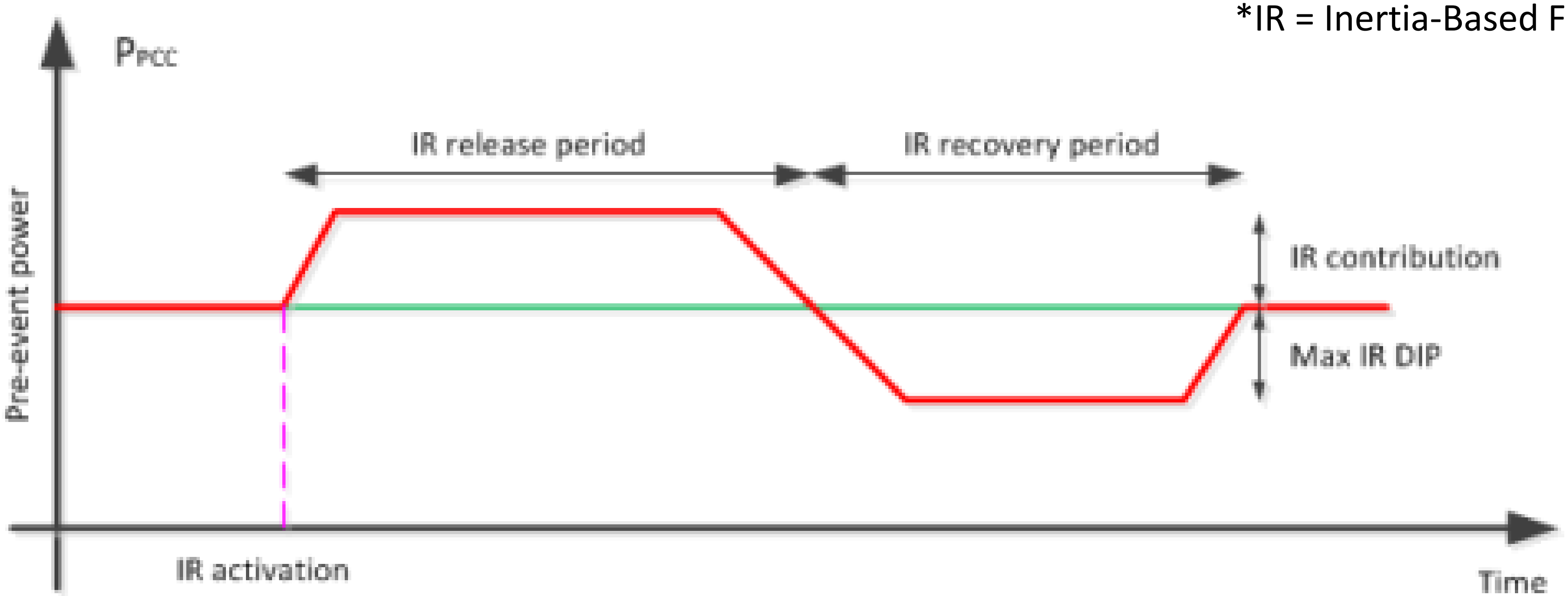
$$Torque_{WTG} \propto Current_{WTG}$$

During inertial response:

- More power demanded → more torque → more current
- Speed drops → even more torque → even more current
- Higher current → more loss → more current to compensate

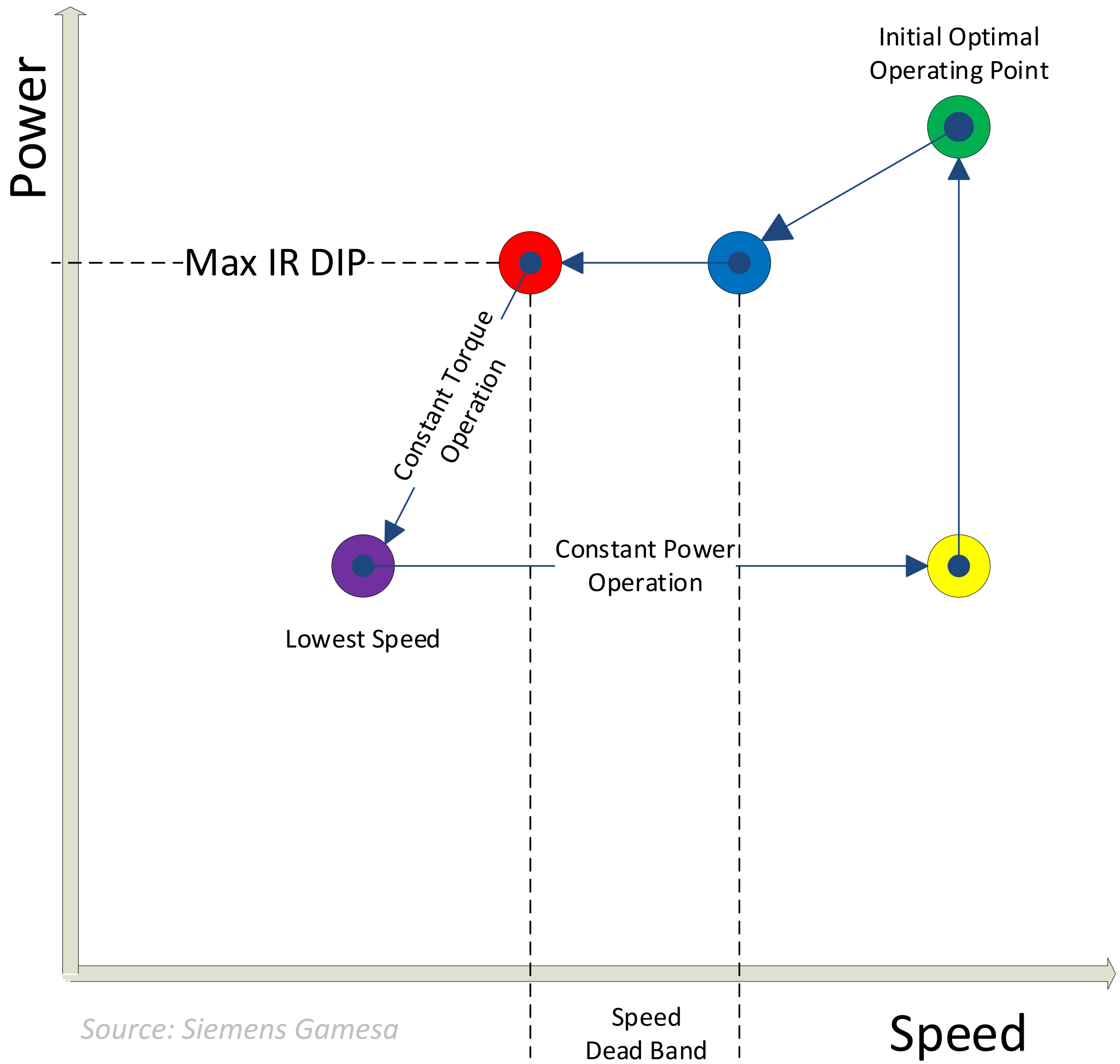
Example of Inertia-Based FFR from Type 4 WTG

*IR = Inertia-Based FFR



Source: Siemens Gamesa

Transition of Operating States during Inertia-Based FFR for WTG

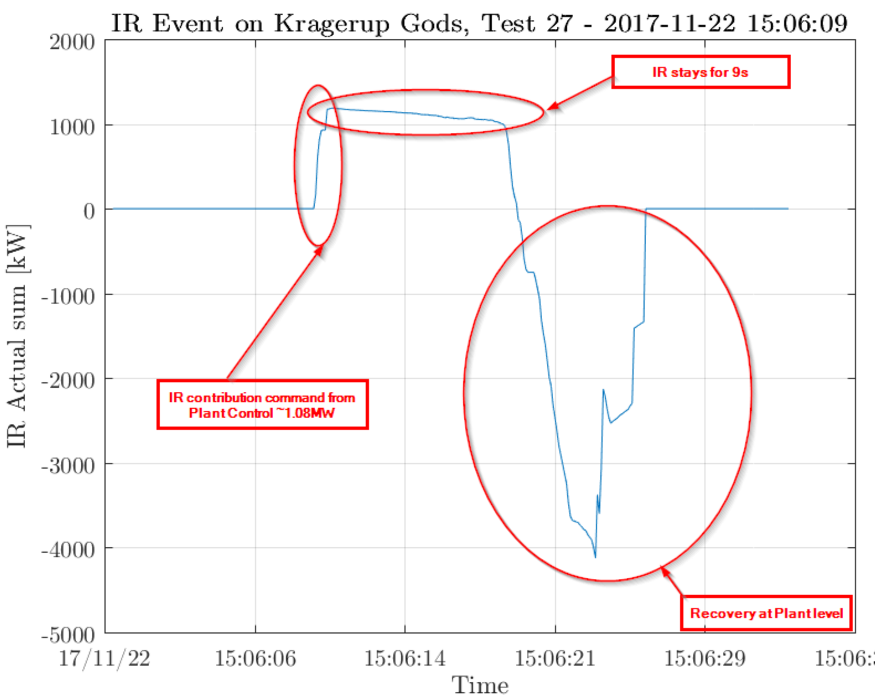


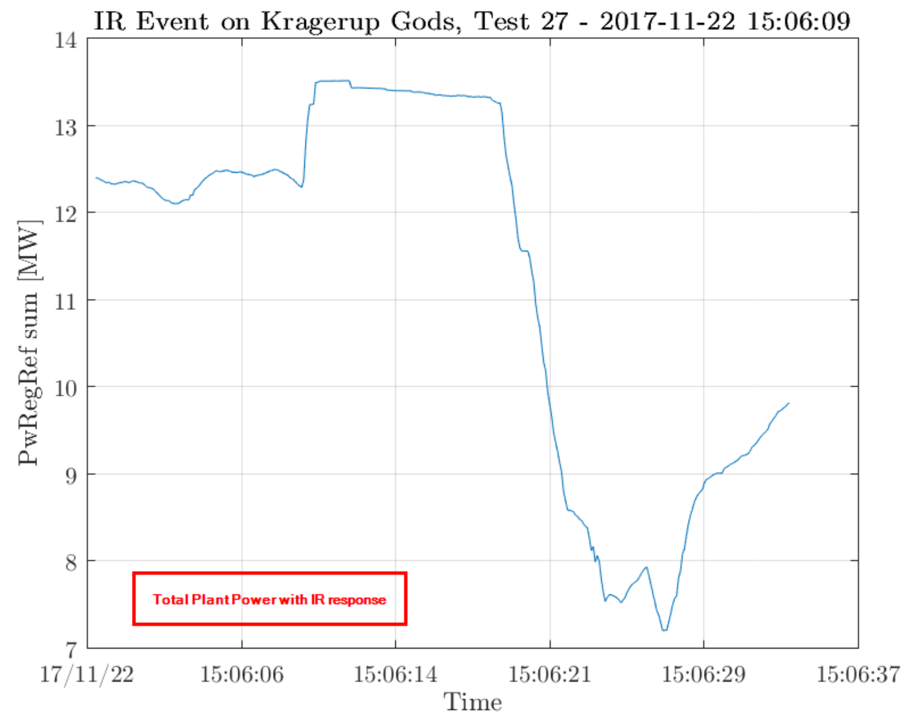
Source: Siemens Gamesa

Field Test of WTG FFR

- 5 WTGs (3.2MW each) at plant (total 16 MW) for testing IR
- IR required to be 6% of plant capacity (~ 1 MW)
- Output power held at FFR output level for 9 seconds
- Plant controller determines contributions from each WTG
- Available inertia-based FFR output power may be different across individual WTGs
- Recovery response can be very different across individual WTGs

Field Test of WTG FFR





Source: Siemens Gamesa

Field Test of WTG FFR

Source: Siemens Gamesa

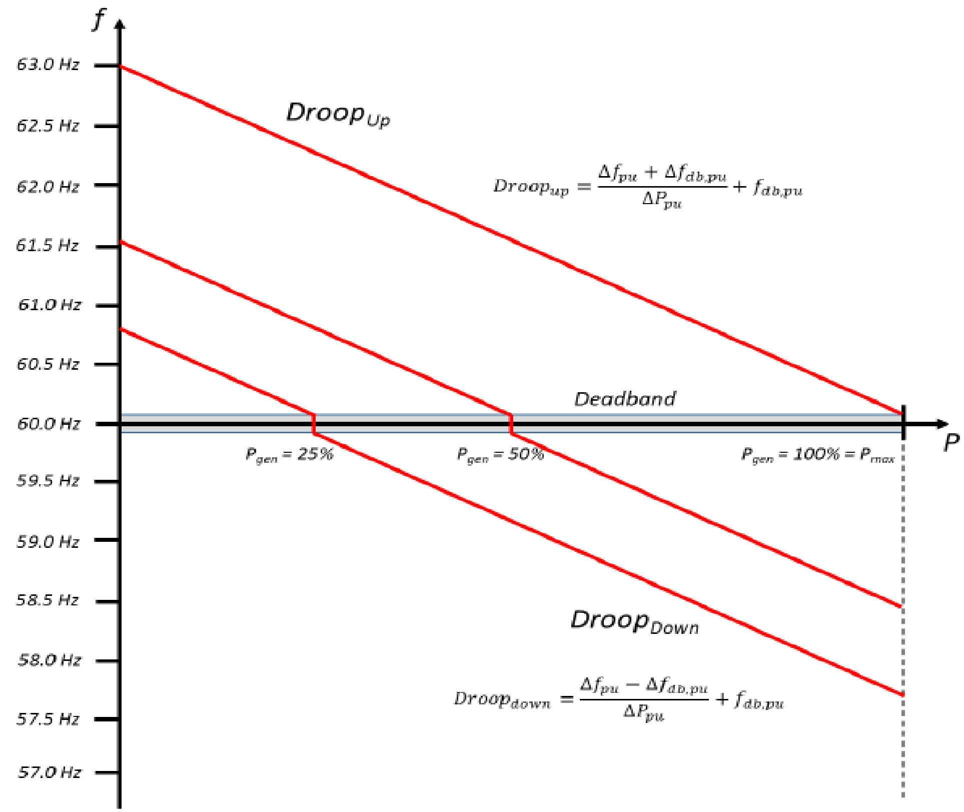
Additional active power drawn from stored kinetic energy in WTG rotors

WTG speeds decline; varies based on available wind speed for each individual WTG

Always followed by WTG speed recovery period, based on WTG pre-disturbance operating point; can possibly be configurable to avoid secondary frequency drop

FFR from Solar PV

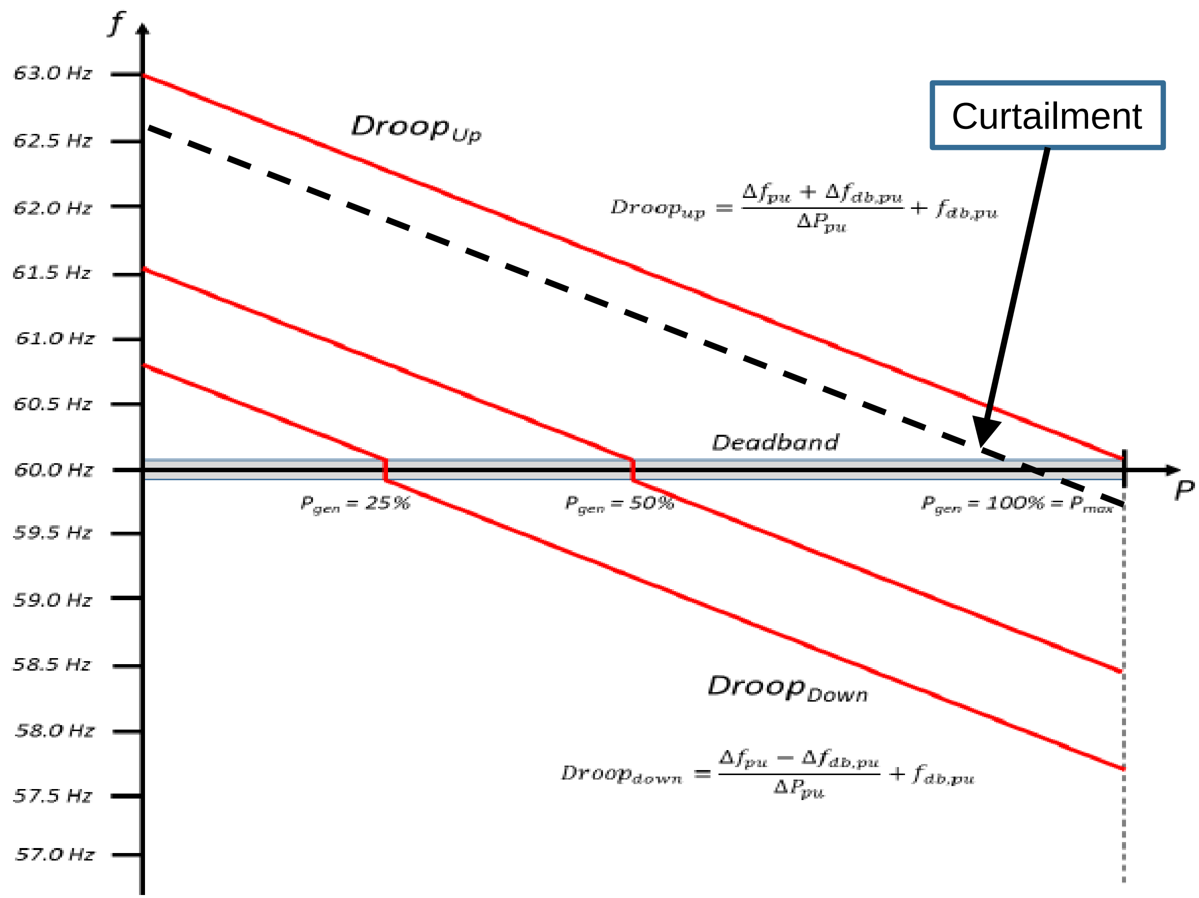
- Solar PV plants can provide FFR on a active power-frequency droop curve
  - Droop control can be implemented in the individual inverters or in the plant-level controller
- Solar PV plants are normally operated at maximum available power.
  - Active power output may also be constrained by the inverter ratings.
  - Therefore, solar PV plants generally provide FFR only for overfrequency events (reducing plant output)



[Source: NERC BPS-connected Inverter-Based Resource Performance Reliability Guideline, Sep 2018]

FFR from Solar PV

- Solar PV plants can also provide FFR for under frequency
  - However, this requires the plant to be curtailed
  - This FFR/PFR can be sustained as long as the solar resource is available



[Source: NERC BPS-connected Inverter-Based Resource Performance Reliability Guideline, Sep 2018]

FFR from BESS and Hybrids

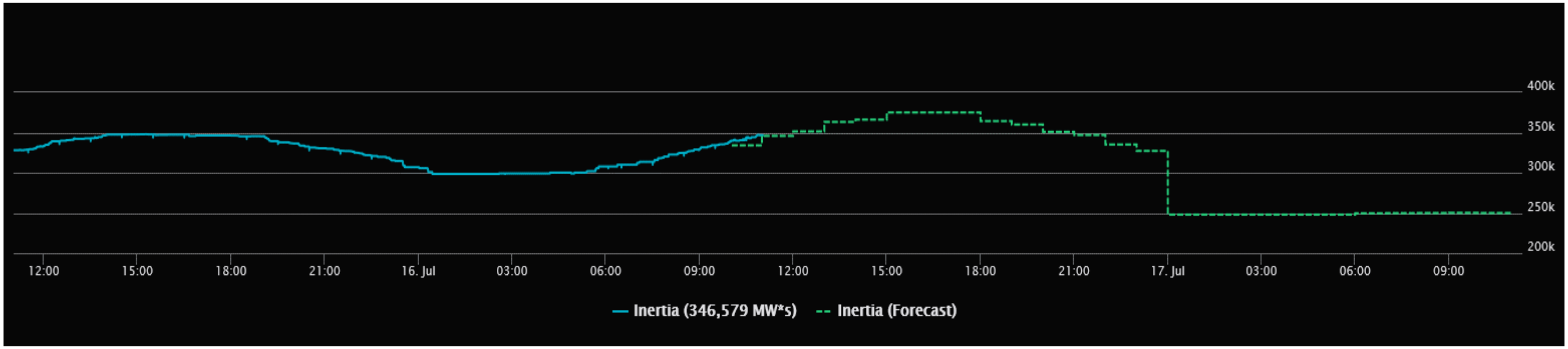
- BESS plants can provide FFR (and PFR) in both discharging (generator) and charging (load) operating modes
  - Duration of FFR/PFR limited by battery state of charge
- Some possible combinations for FFR for BESS plants:
  - Discharging ("operating as a generator"):
    - Overfrequency: **Decrease** power **out**put
    - Underfrequency: **Increase** power **out**put
  - Charging ("operating as a load"):
    - Overfrequency: **Increase** power **in**put
    - Underfrequency: **Decrease** power **in**put
- Hybrid power plants can combine technology benefits
  - E.g., utilize BESS to provide FFR/PFR when solar PV operating at maximum available power

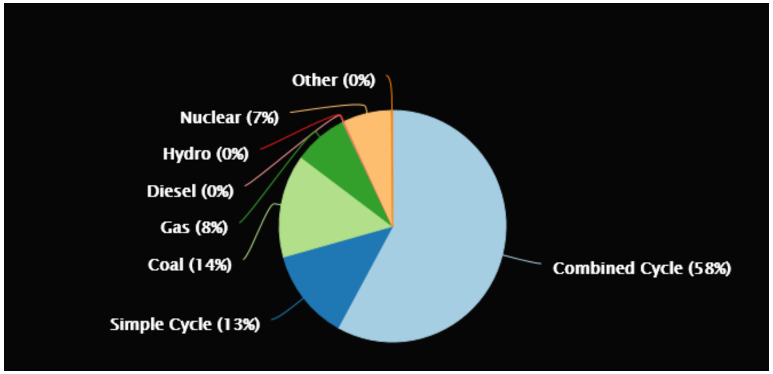
Application of Fast Frequency Response in ERCOT

Julia Matevosyan, ERCOT

ERCOT Inertia Monitoring

ERCOT implemented inertia monitoring and forecasting in the control room in 2016, summing inertia of online synch. generators



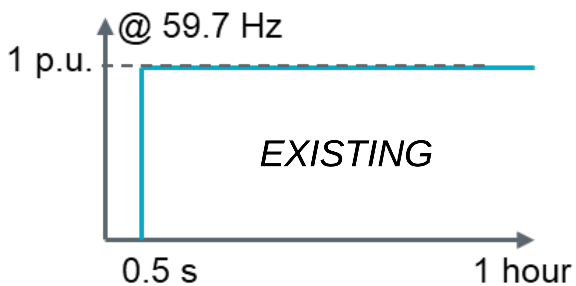


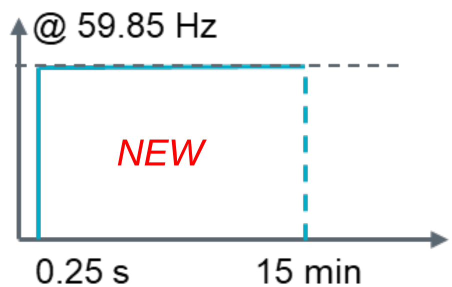
Source: ERCOT

- Critical inertia determined as 100 GW*s based on stability analysis for 2750 MW trip
- Largest credible contingency is monitored in real time and critical inertia adjusted accordingly
- ERCOT operators can bring additional generation online if system inertia is approaching critical levels

ERCOT FFR Market Product

- ERCOT procures frequency responsive reserve to prevent the operation of UFLS for the largest credible contingency
  - Simultaneous trip of two largest nuclear units = 2750 MW
- Historically, a portion of this reserve was provided by industrial loads through fast step-response to a frequency trigger
- On 3/1/2020, new fast frequency response product was added with faster response time and earlier frequency trigger
- Amounts of procured frequency response are based on inertia conditions and coordinated between FFR sub-products and PFR

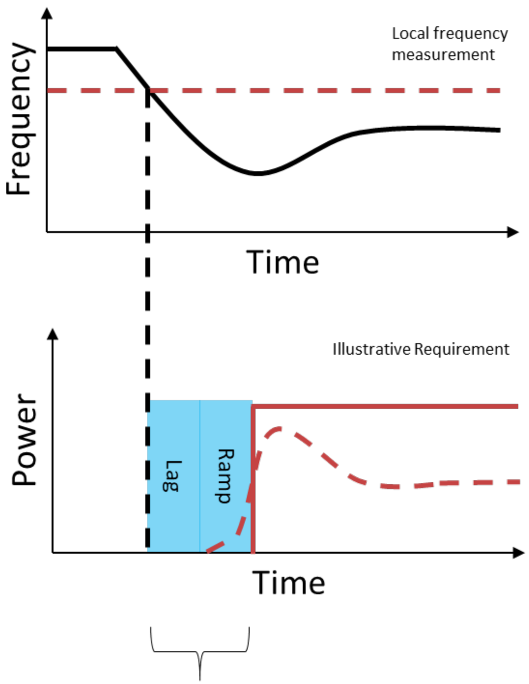




Fast Frequency Response Around the World

Papiya Dattaray, EPRI

FFR: European Overview



Frequency Trigger

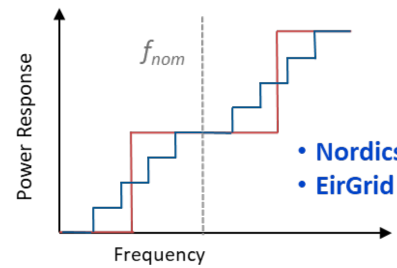
EirGrid:	**49.985 to 49.8 Hz (dynamic)** **49.8 to 49.3 Hz (static)**
National Grid ESO[1]:	**49.9 to 49.5 Hz (dynamic)** **49.6 Hz (static)**
Nordic TSOs:	**49.7, 49.6 and 49.5 Hz (static)**

Static
or
Dynamic

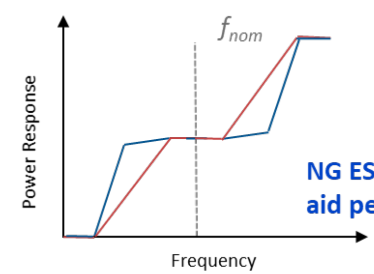
1 step or many …?

Should it be Symmetrical…?

1 characteristic or 2 …?



- **Nordics use 1 step Static**
- **EirGrid prefer multi-step**



NG ESO suggest 'creep' to aid performance monitoring

Full Response Time
Lag Time + Ramp Time

EirGrid:	**0.1 to 2 s**
National Grid ESO[1]:	**0.5 to 1 s**
Nordic TSOs:	**0.7 to 1.3 s**

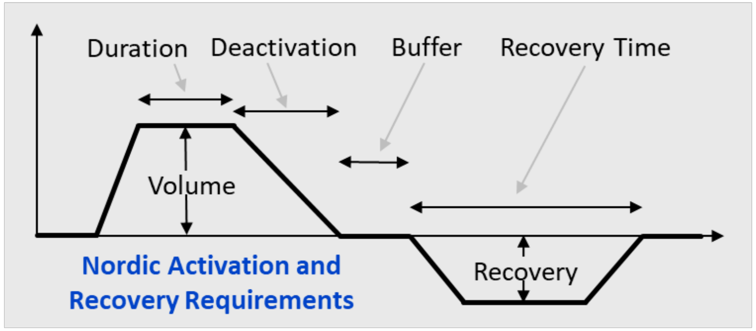
[1] these values reflect NG ESO's new services that are under development

Source: EPRI

FFR: European Overview

FFR symmetry varies between TSOs

- **Eirgrid**: under DS3 FFR is for under frequency only.
  - Separate 'volume capped' competition contracted limited volume of over frequency FFR from BESS.
- **Nordics**: FFR is for under frequency only
  - studies indicated over frequency well managed without FFR
- **National Grid ESO**: developing new FFR services
  - FFR Containment will have separate under and over frequency
  - FFR Moderation service will be symmetrical



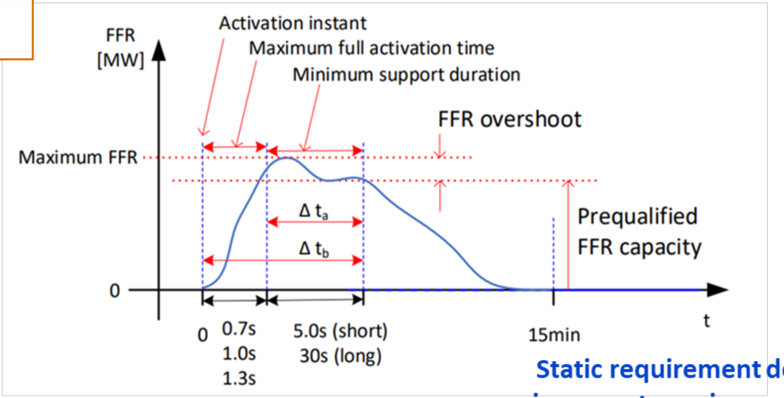
https://www.fingrid.fi/globalassets/dokumentit/en/electricity-market/reserves/fast-frequency-reserve-solution-to-the-nordic-inertia-challenge.pdf

Duration and recovery can be as important as activation

FFR in Nordic system compliments FCR-D

the FFR is static to simplify design and avoid closed loop dependency between FFR and FCR-D,

Source: EPRI



Static requirement doesn't impose step-wise provision

https://www.svk.se/siteassets/aktorsportalen/tekniska-riktlinjer/ovriga-instruktioner/technical-requirements-for-fast-frequency-reserve-provision-in-the-nordic-synchronous-area-1.pdf

Wrap Up – Key Findings and Takeaways

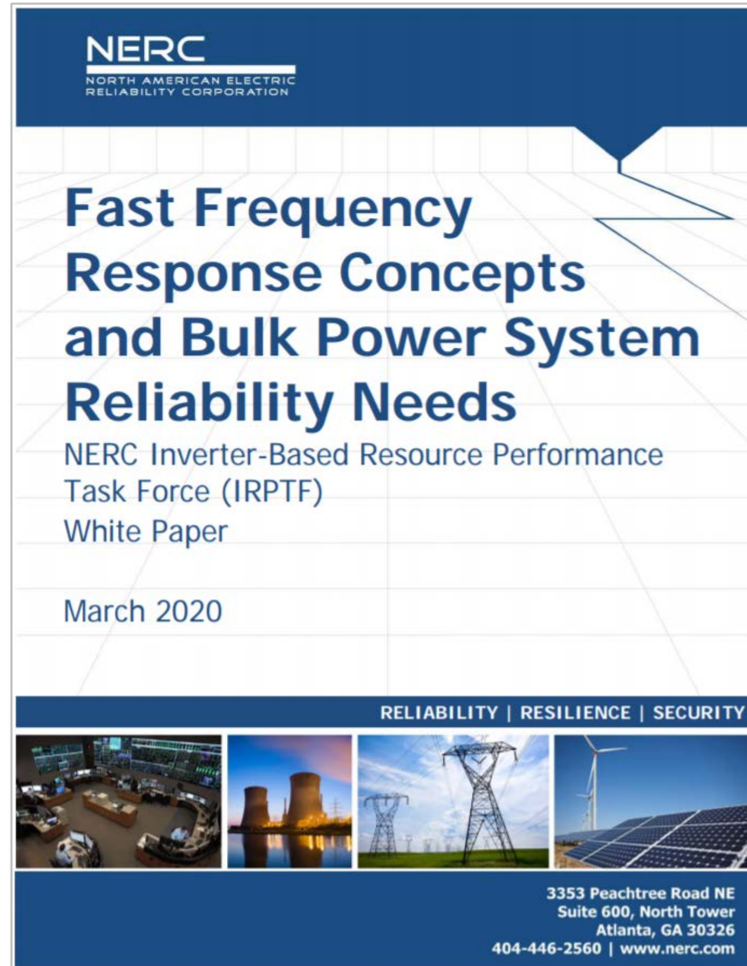
Ryan Quint, NERC

Key Takeaways

- Changing resource mix, changing grid dynamics
  - ROCOF, system inertia, available reserves, speed/magnitude of response
  - System reliability needs should drive the development of new tools, market products, requirements (differ for each Interconnection)
    - Large systems may not need FFR in the near term
- Inverter-based resources have the capability to provide PFR and FFR (solar PV, wind, battery storage, etc.)
  - Different technologies, different control strategies
  - Sustained PFR/FFR requires “headroom” (presently not mandated); non-sustained FFR different based on technology
  - Should be coordinated with other inverter controls
  - Should be studied by BA and coordinated across Bas
- Critical inertia studies and real-time inertia monitoring

NERC References

- NERC IRPTF Webpage
  - White Paper: FFR Concepts and BPS Reliability Needs
- NERC Reliability and Security Guidelines
  - Reliability Guideline: BPS-Connected Inverter-Based Resource Performance
  - Reliability Guideline: Improvements to Interconnection Requirements for BPS-Connected Inverter-Based Resources
- Summary of Activities: BPS-Connected Inverter-Based Resources and DERs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NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

Fast Frequency Response Concepts and Bulk Power System Reliability Needs

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

March 2020

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Questions and Answers

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