Frequency Response

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DISCLAIMER

This work was produced by Julia Matevosyan under the Women in Power System Transformation (PST) initiative, funded by the United States Agency for International Development (USAID) under the USAID-National Renewable Energy Laboratory (NREL) Partnership.

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Fundamentals of Frequency Control

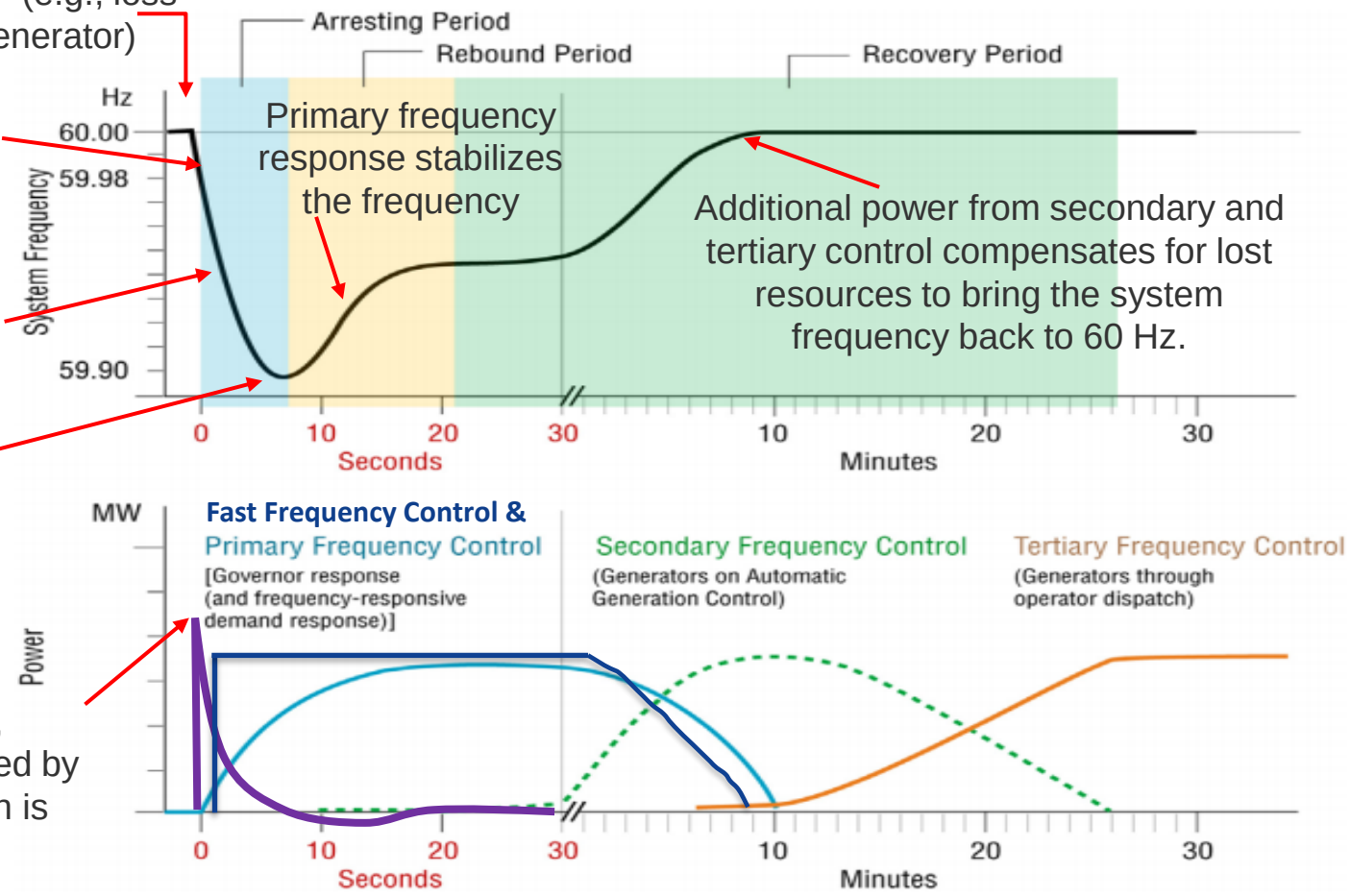
Disturbance – (e.g., loss of large generator)

Synchronous Inertial Response sets initial slope

Fast frequency response slows down initial rate of change of frequency,

and with initial primary frequency response, establishes the minimum frequency point ("nadir").

Synchronous Inertial Response is "instant", uncontrolled, and dominated by accelerating power which is proportional to $d\omega/dt$.



Source: Eto, et al. (2010): Use of a Frequency Response Metric to Assess the Planning and Operating Requirements for Reliable Integration of Variable Renewable Generation, modified by Nick Miller and Julia Matevosyan

Frequency Response

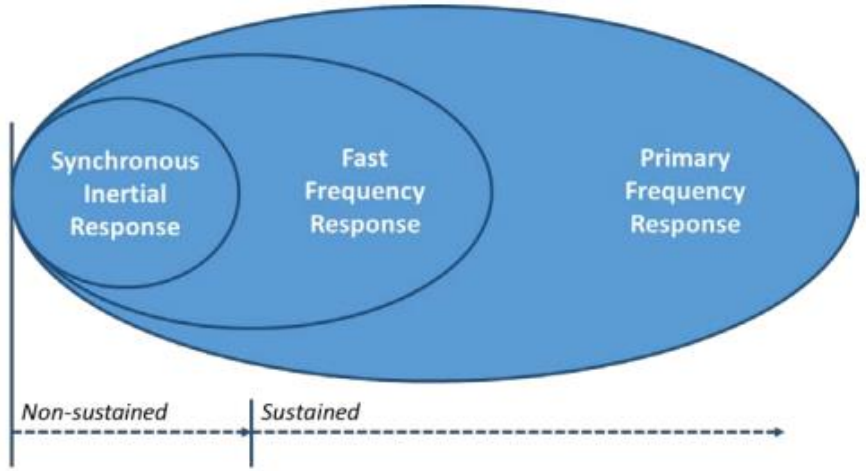


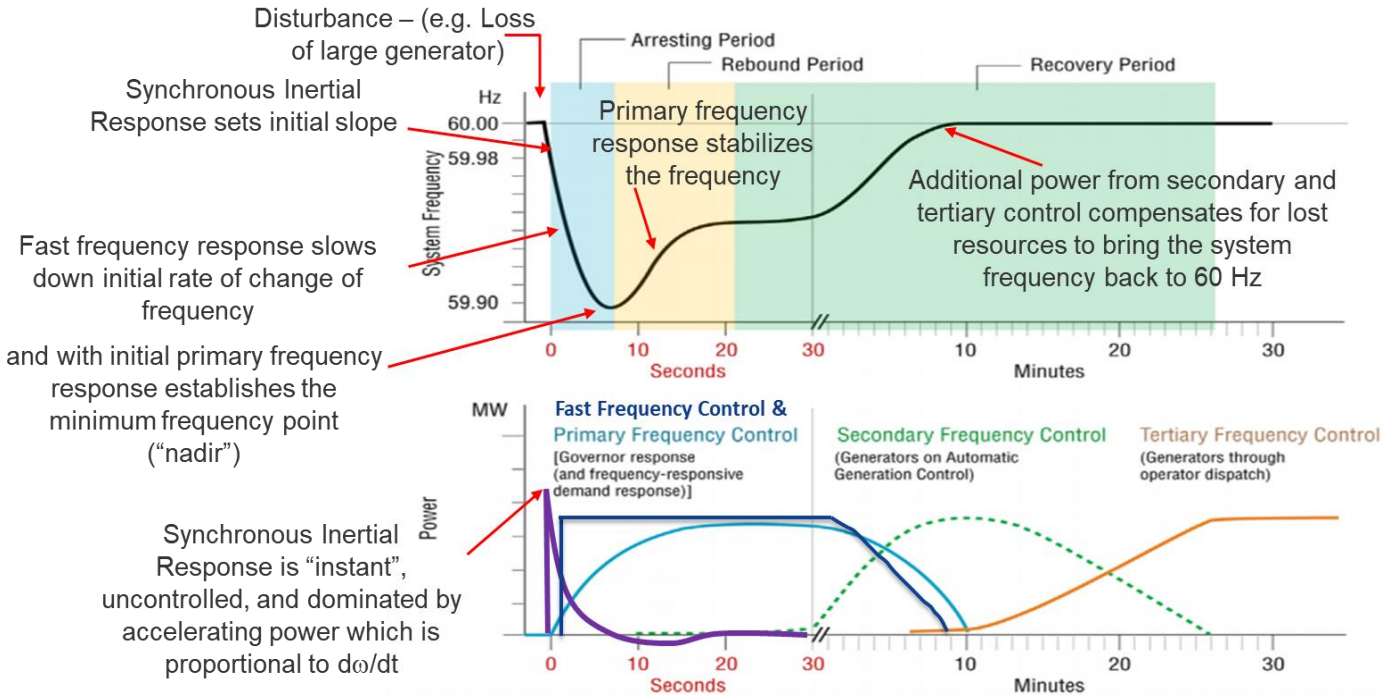
Figure 2.1: Simultaneous Contributions of Inertia Response, PFR, and FFR

Synchronous Inertial Response (SIR) – determines Rate of Change of Frequency (RoCoF)

Fast Frequency Response (FFR) – slows down RoCoF

Primary Frequency Response (PFR) also called **Frequency Containment Response (FCR)** – arrests (or contains) and stabilizes system frequency

Source: NERC White Paper: [Fast Frequency Response Concepts and Bulk Power System Reliability Needs]

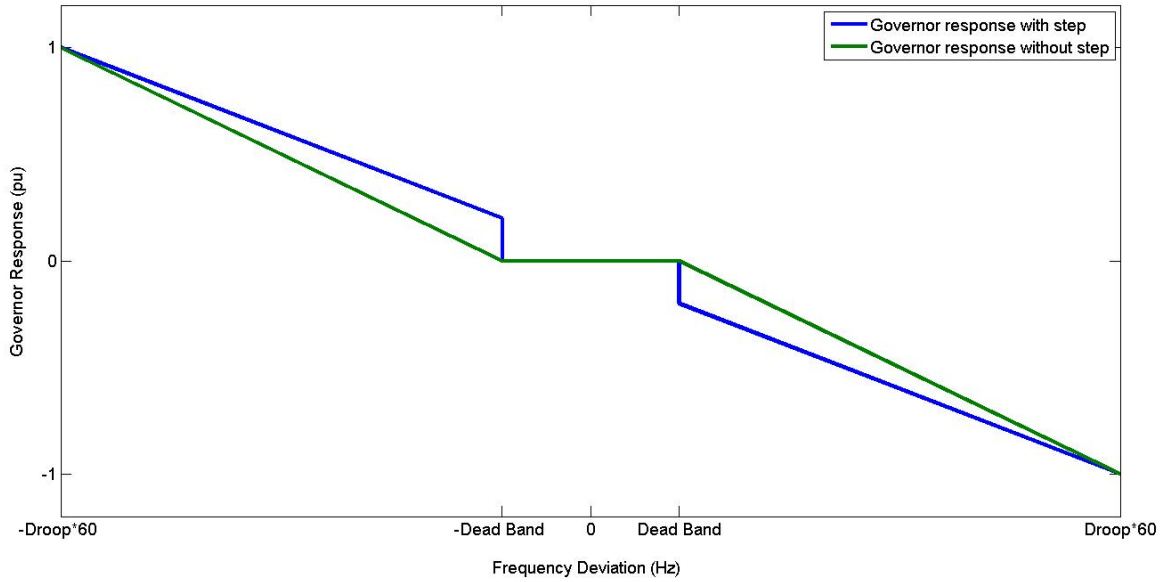


- Frequency response should be sustained and allow frequency recovery to nominal following a sudden loss of generation or load.
- SIR/FFR/PFR can work in coordination to support frequency.
- Systems with large synchronous inertia (low initial RoCoF) do not have a fundamental need to distinguish between FFR and PFR.
- In low inertia systems, FFR is necessary to slow down RoCoF

Governor Response of Synchronous Generators

- Synchronous generators are capable of providing frequency containment response using speed governors.
- Speed governors vary prime mover output automatically for changes in system frequency.
- The rate and magnitude of the governor response can be tuned for the characteristics of the generator and the power system to which it is connected.
- To reduce activity of controllers for normal frequency variations, a deadband may be introduced.
- In the United States, typical deadband is ±36mHz around 60 Hz, while Electric Reliability Council of Texas (ERCOT) uses ±17 mHz deadband.
- The rate of response is defined by a droop, i.e. percent of frequency change that results in output change of 100%.
- Typical droop setting used is 5%.

Source: [WECC Tutorial on Speed Governors]



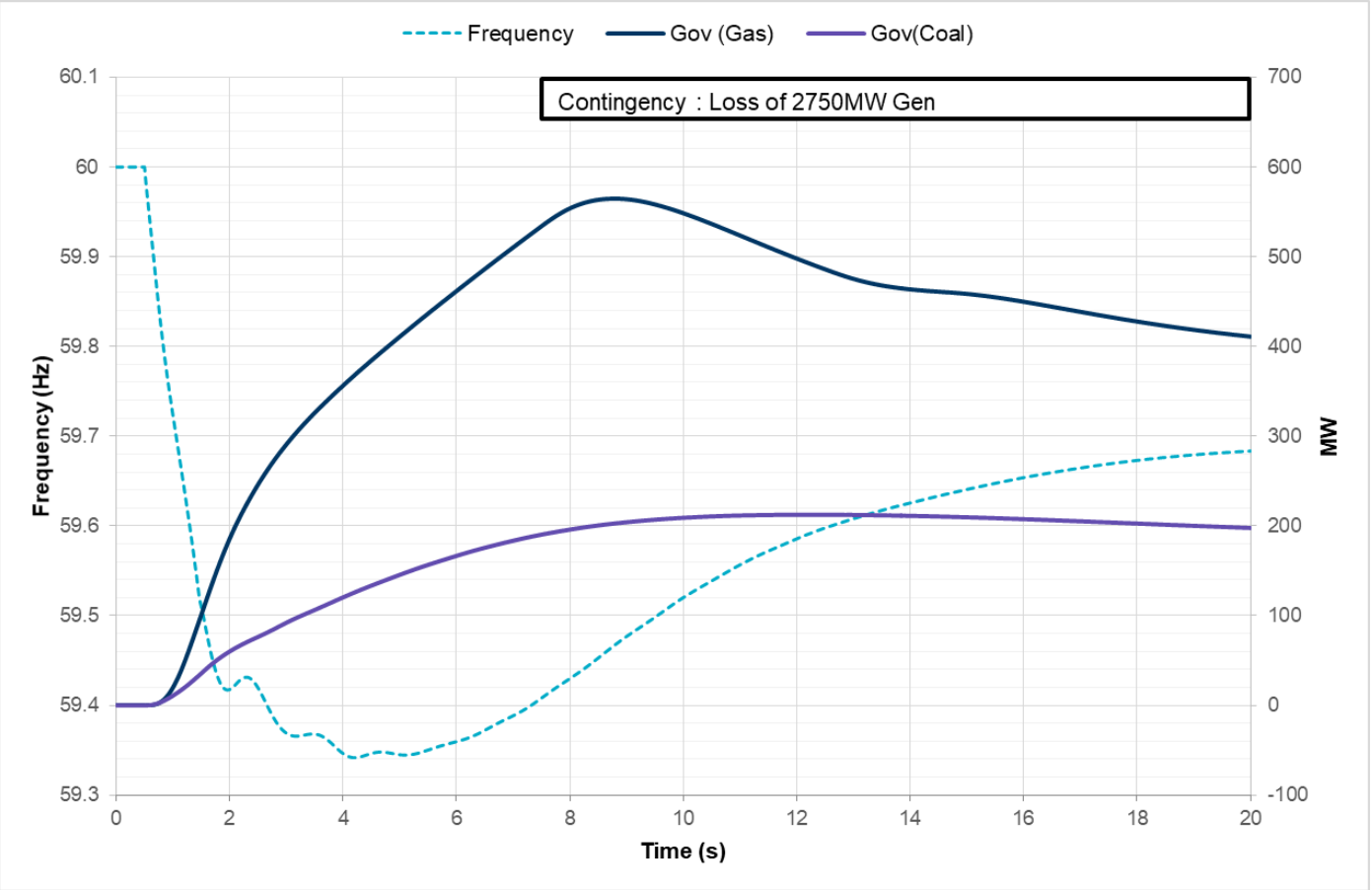
Governor response with step

$P_{Gov} = -Rated\ Power * \Delta f / (60 * \text{droop})$

Governor response without step

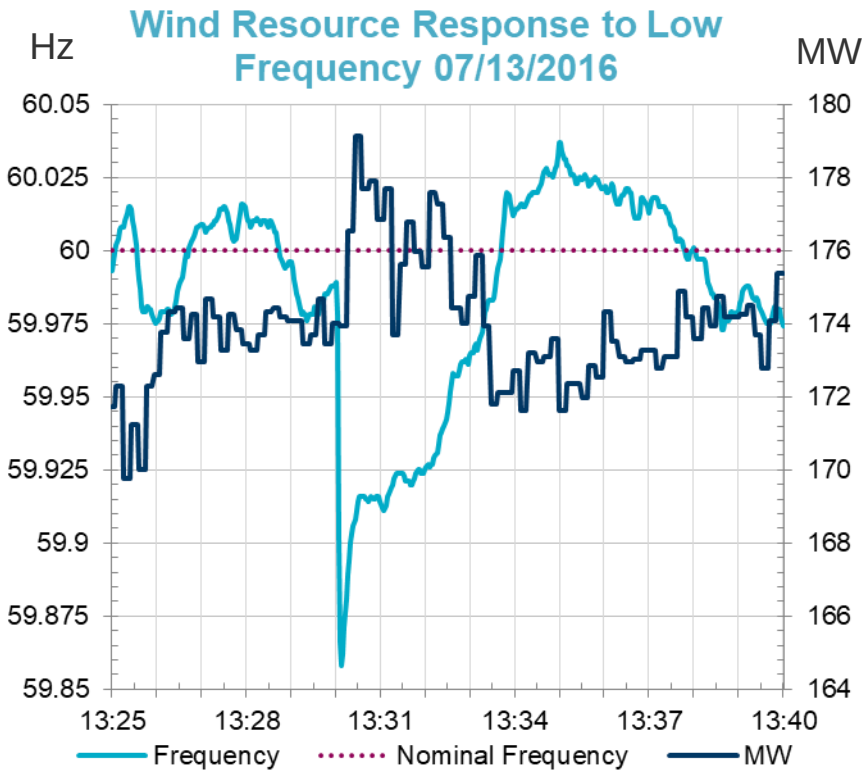
$P_{Gov} = -Rated\ Power * (\Delta f \pm deadband) / (60 * droop - deadband)$

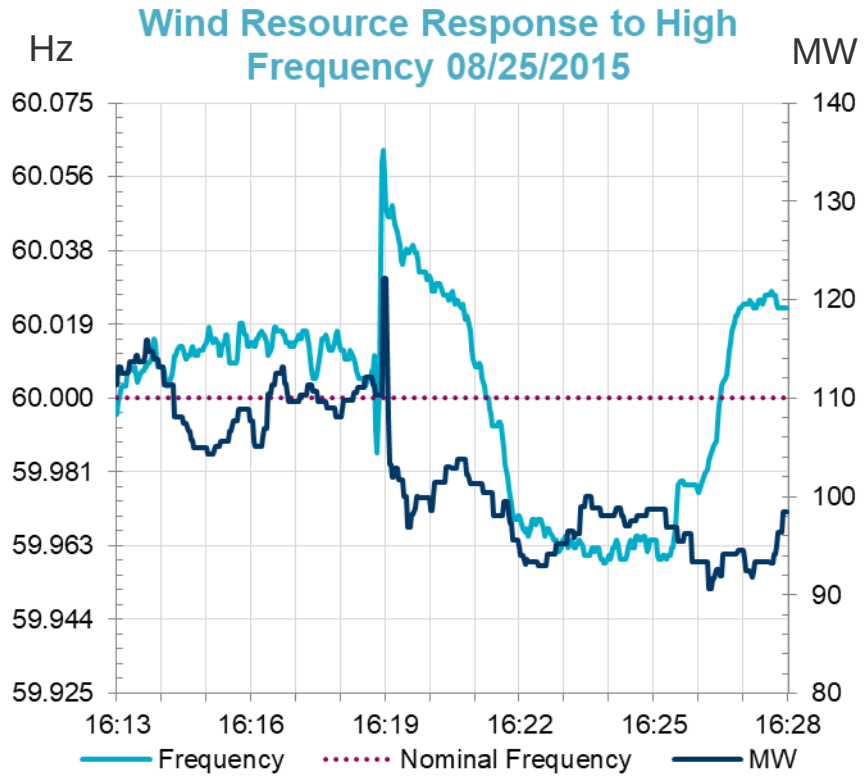
Speed of Governor Response



Speed of governor response varies depending on generator technology

“Governor-like” Response Form Inverter-Based Resources (IBRs) – Example From ERCOT

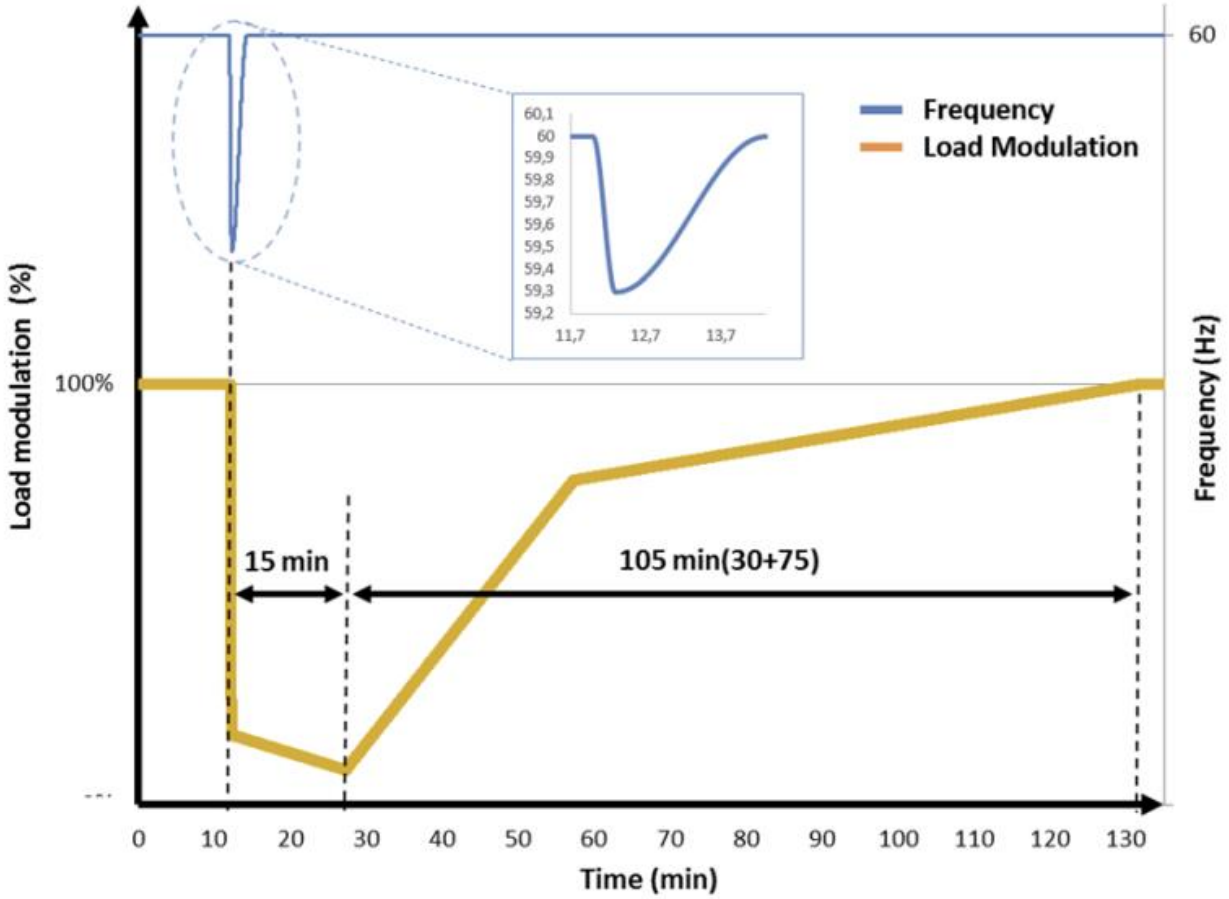




Reminder: Governor Response, “Governor-like” Response, Primary Frequency Response (PFR) are all types of Frequency Containment Response (FCR) used to arrest/contain and stabilize system frequency

“Governor-like” Response from Load – Example from Hydro Quebec

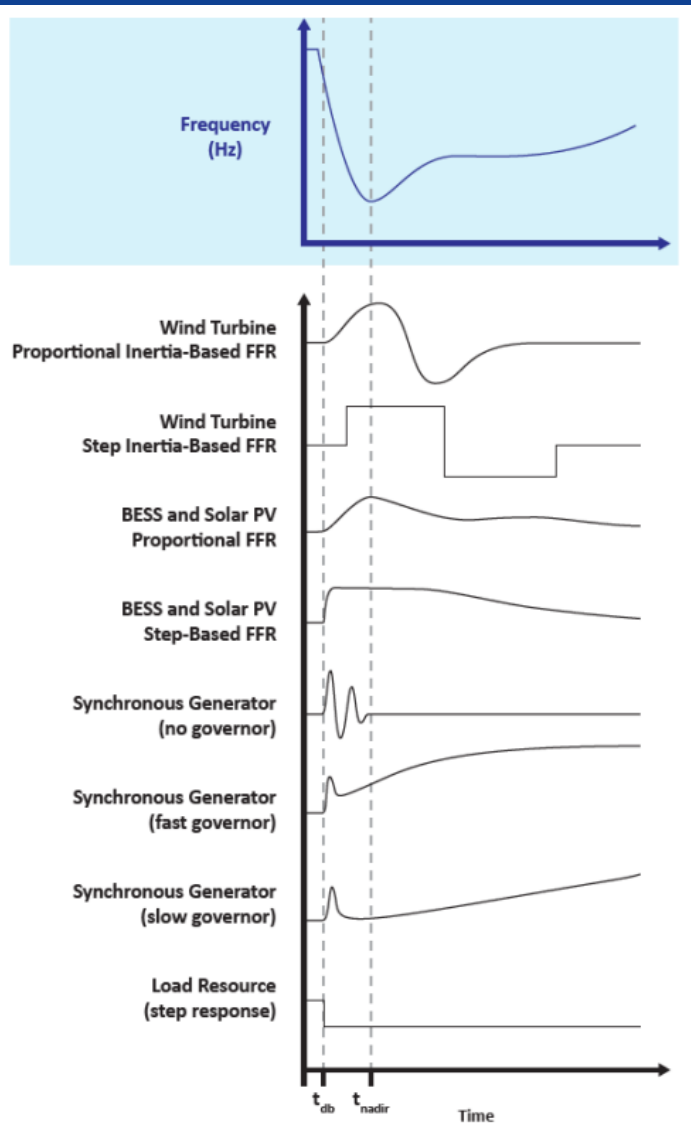
- Hydro Quebec implemented a pilot for frequency sensitive control on residential electric hot water heaters.
- Proportional response to frequency is achieved in less than 250 ms.
- The load modulation is as follows: droop of 1%, modulation starts at 59.8 Hz, end of load modulation at 59.2 Hz, load modulation is linear between 59.8 and 59.2 Hz.
- The response is sustained for 15 minutes after which the load gradually returns to pre-disturbance level.



Source: F. Monette, P. Cadieux, A. Moreau, S. Jasmin Using Smart Loads to Improve Frequency Response at Hydro-Quebec and Enhance Renewable Energy Integration

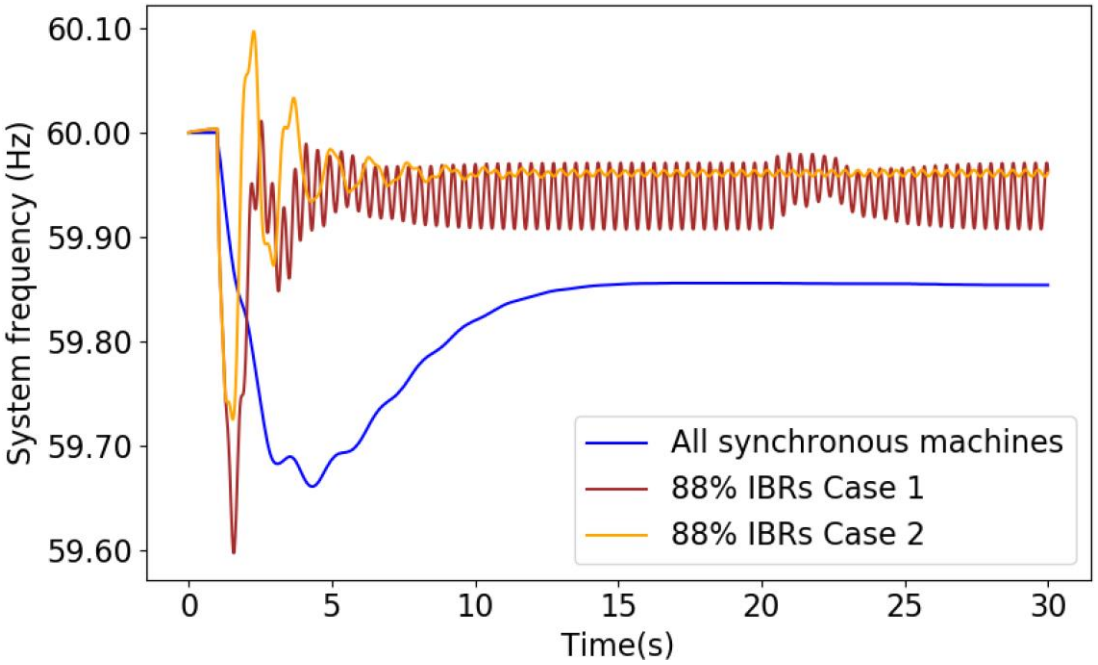
Fast Frequency Response

- Fast Frequency Response: power injected to (or absorbed from) the grid in response to changes in measured or observed frequency (or RoCoF) during the arresting phase of a frequency excursion event to improve the frequency nadir or initial RoCoF.
- Should be sufficiently fast. The term “fast” is relative to each individual system and should not be generalized.
- FFR can be obtained through numerous control philosophies (i.e., based on magnitude of frequency deviation, RoCoF, or other factors) that each can help during the arresting phase of a frequency excursion. These various types of controls should not necessarily be dictated unless there is a reliability need.
- Should not interfere with or degrade the stability of the system. For this reason, faster response may not be desirable in some areas, such as those with low system strength.



Location of Delivery of FFR Can Be Important

- Location of fast frequency response with regard to disturbance is important to consider.
- At a given location, there can be a finite speed of FFR that is possible, while maintaining stability.
- Fast frequency response provided by IBRs in remote areas can deteriorate the damping of local modes associated with electromechanical dynamics.
- Electric Power Research Institute (EPRI) has developed analytical methods that evaluate if delivery of FFR can deteriorate the system damping, and if so, what mitigation strategies are available.



Case 1 – Only IBRs located electrically far away provide response

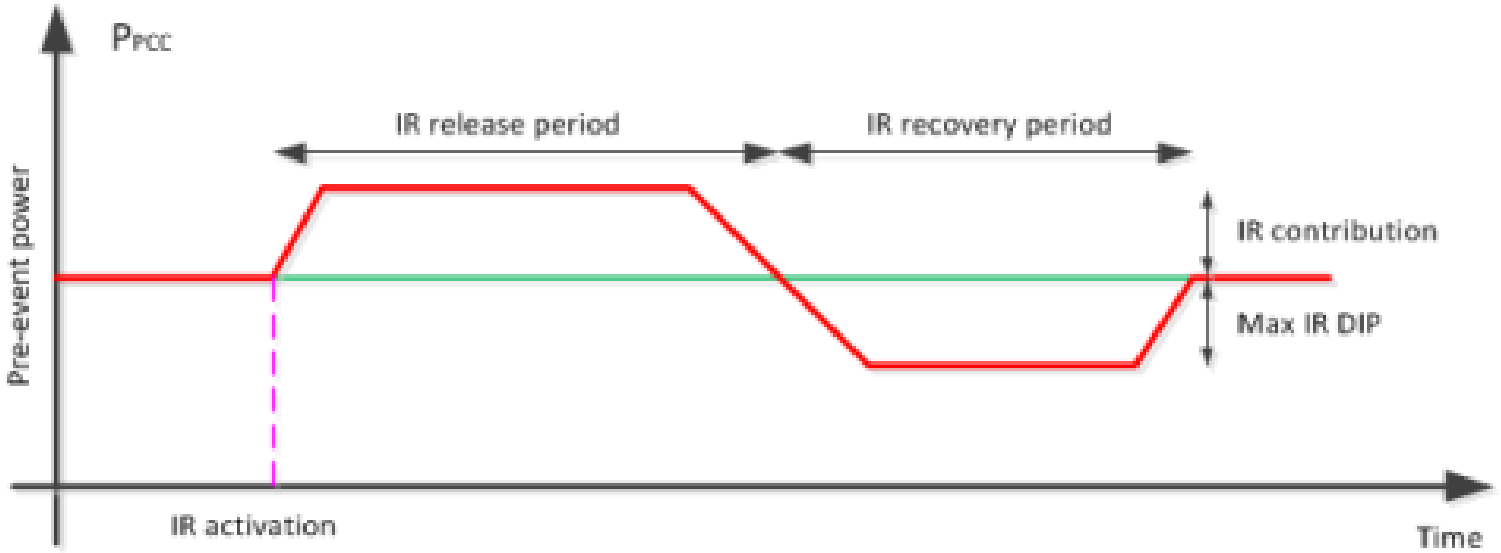
Case 2 – IBRs located nearby also provide response

Source: D. Ramasubramanian, P. Mitra, P. Dattaray, M. Bello, V. Singhvi, “Delivery of Primary Frequency Response over Weak Electrical Paths,” *2021 IEEE Madrid PowerTech*, 2021

G. Misyris, D. Ramasubramanian, P. Mitra, and V. Singhvi, “Locational Aspect of Fast Frequency Reserves in Low-Inertia Systems," *2022 IREP Symposium*, Banff, Canada, 2022

Inertia-Based FFR From Wind Generation

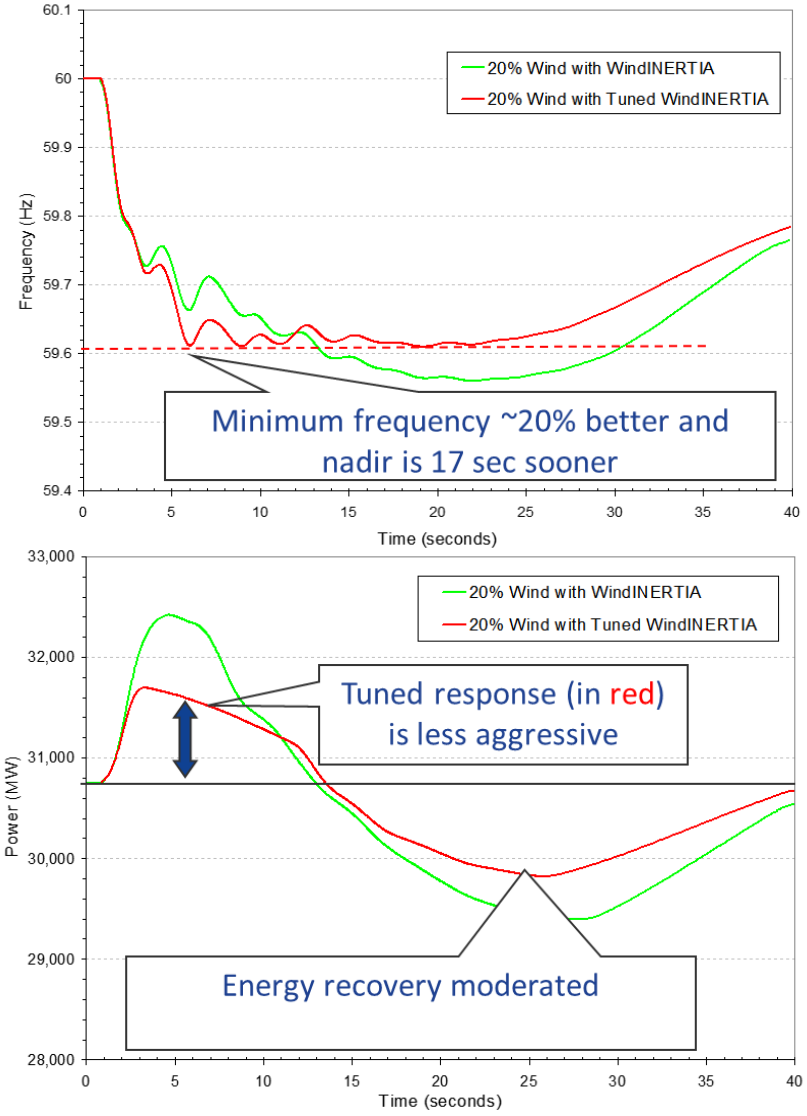
- Control algorithm to extract kinetic energy stored in the rotating mass of wind turbines and provide temporary active power overproduction to the grid in response to low frequency events.
- Frequency needs to be measured and event identified (>100 ms)
- Then, the delivery of active power from the wind turbine to the grid is controlled by power electronics and is almost instantaneous (few cycles).
- Wind turbine needs to return to its design speed, active power injection may be reduced below pre-disturbance level – recovery periods.



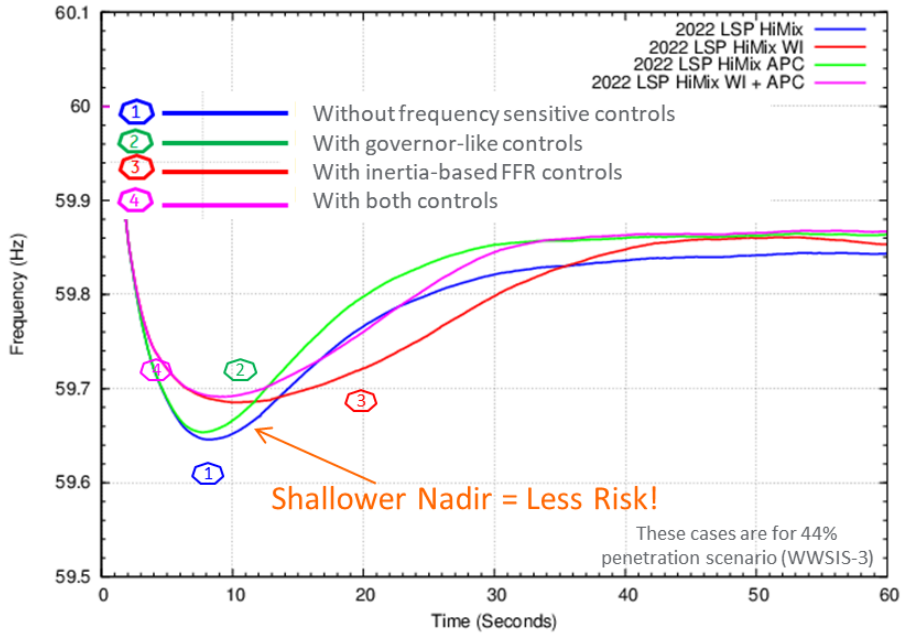
Non-sustained FFR that is depleted prior to the post recovery period should not negatively impact frequency during the arresting or recovery periods, nor should it negatively impact overall system frequency control.

Source: NERC Industry Webinar, White Paper: Fast Frequency Response Concepts and Bulk Power System Reliability Needs

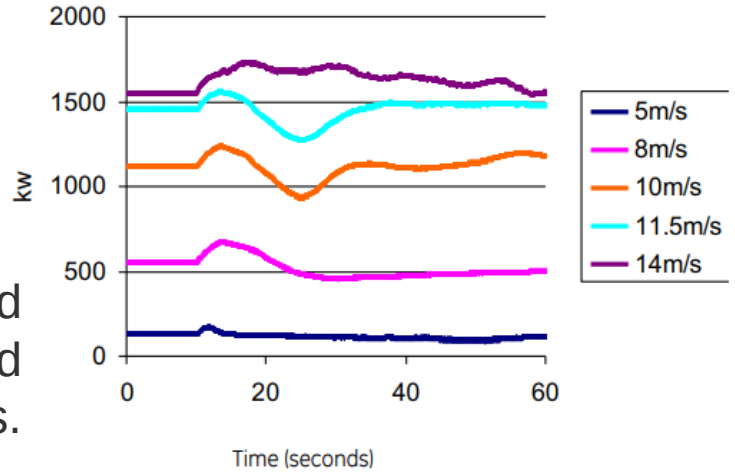
Inertia-Based FFR From Wind Generation



Tuning Inertia-Based FFR further improves frequency nadir and reduces impact of recovery energy.



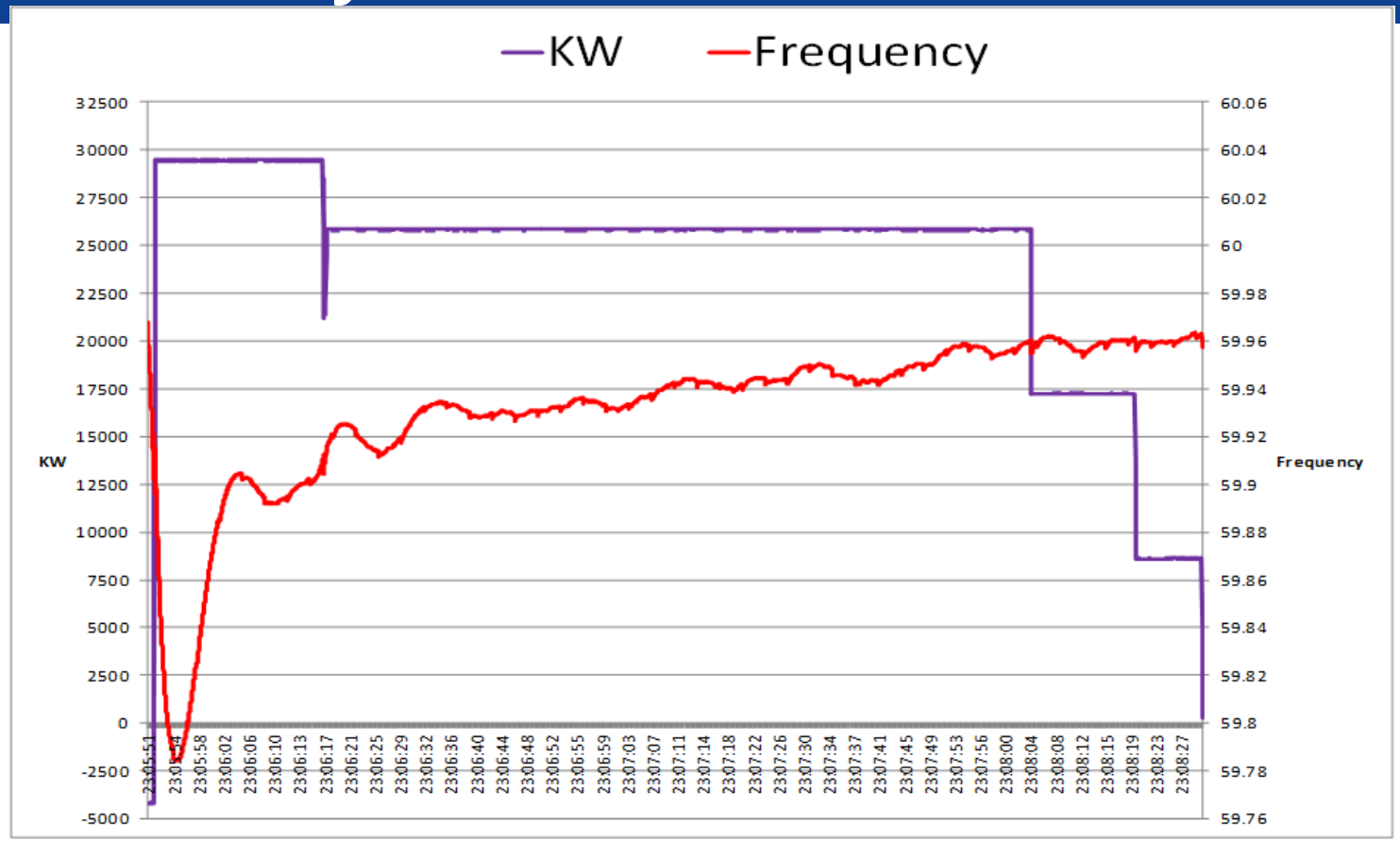
Effectiveness of Inertia-Based FFR depends on wind conditions.



Source: GE Energy Consulting

Frequency Response From Solar Photovoltaics (PVs) or Battery

- Solar PV and battery storage can provide FFR (as well as FCR).
- Battery storage can provide frequency response both from discharging (generator) and charging (load) operating modes.
- Duration of response is limited by battery state of charge
- Hybrids (i.e. battery storage + another generation type) can be used to combine technology benefits for provision of frequency control.

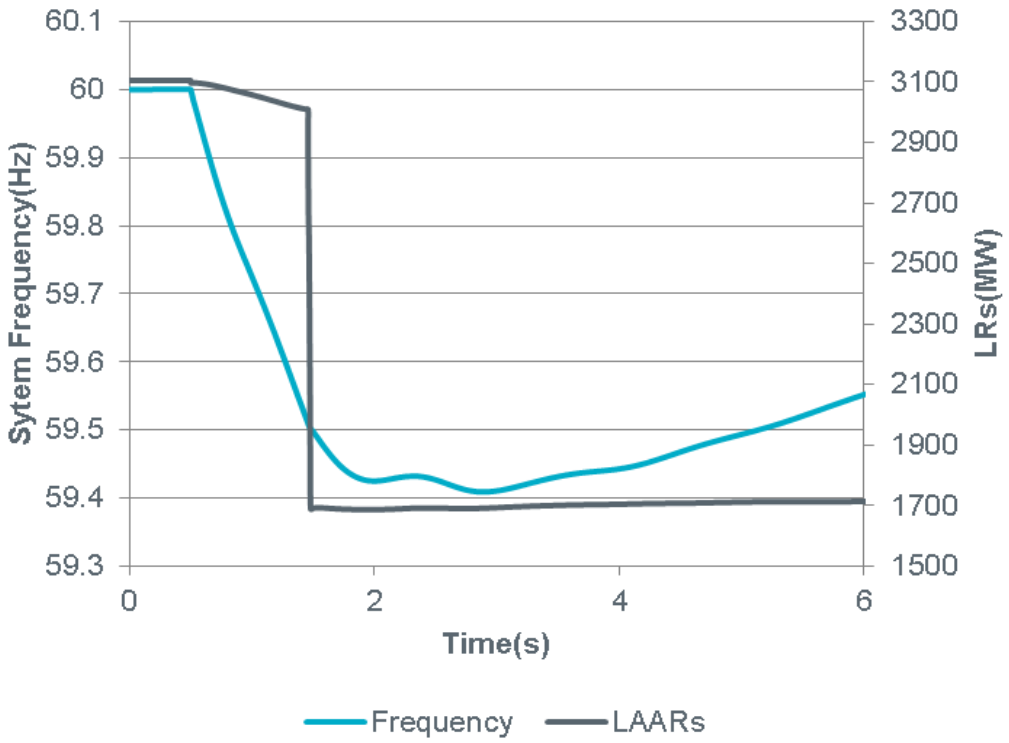


- Frequency response by a battery in ERCOT during a frequency event
- The battery responded to a frequency trigger at 59.91 Hz
- The requirement for full response was 1 second. However, it detected the event and fully responded in 92 milliseconds (ms)

FFR From Load Resources – Example From ERCOT

From Load Resources (LR):

- Triggered by under frequency relay (at 59.7Hz)
- Delivered within **0.5 second**



Load Resources providing frequency response are single-site loads (no aggregation), 100-250 MW:

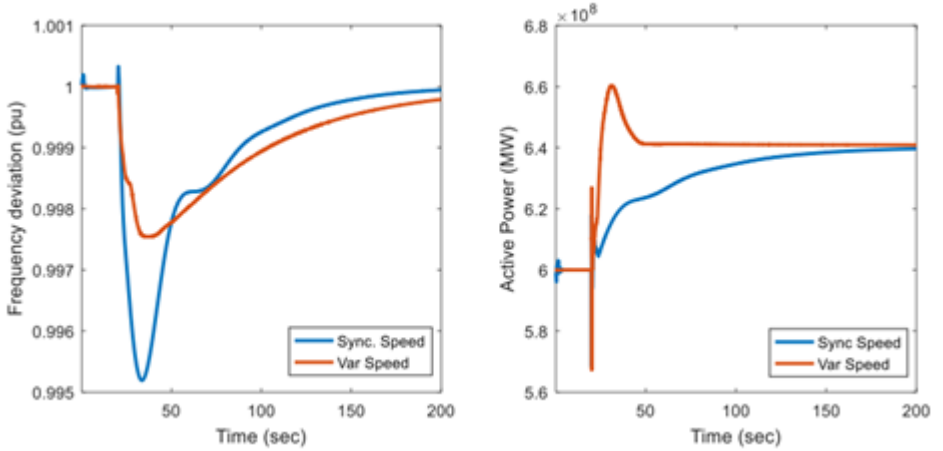
- Industrial process plants that produce chemicals, each site >150 MW, and consist of several process lines, each about 50 MW
- Air separation plants extracting industrial gasses, each site ≤ 100 MW
- Natural gas compression sites that are part of pipeline operation
- Oil field loads (from couple of kW to tens of MW)
- Industrial process loads (i.e. cement plants, manufacturing plants)
- Very few large commercial sites, mainly data centers

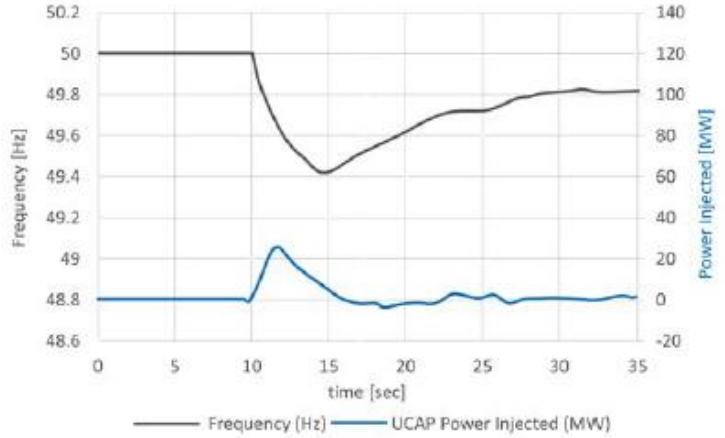
The participation from broader range of customers is limited due to:

- Instantaneous interruption that a Resource should be able to withstand and
- Costs of real-time telemetry equipment required by ERCOT.

Emerging Technologies Providing Frequency Response

- **Ultracapacitors (or Supercapacitors):** can provide fast frequency response (10-20 ms for 100% response). However, response can't be sustained beyond a few tens of seconds; can be combined with other resources for sustained frequency response
- **Flywheel:** fast response time (<10 ms for 100% response) and high power to energy ratio. High power flywheels can also recharge in seconds. Typical sustain time is 15 minutes
- **Variable Speed Pumped Hydro Storage:** can provide frequency response similar to wind turbine and variable speed drive motors
- **Compressed Air Storage:** frequency response similar to other synchronous generators governor response and Load Resource frequency containment response
- **High-voltage Direct Current (HVDC) Links:** can provide FFR or FCR similar to Solar PV or Battery Storage





* Source: R Bessa, C Moreira, B Silva, J Filipe and N Fulgêncio - IOP Conf. Series: Journal of Physics: Conf. Series 813 (2017) - Role of pump hydro in electric power systems
** Source: Maxwell Technologies

Summary of FCR and FFR Capabilities

Technology	Synchronous Inertia	FCR			FFR		
		Type	Time to full response	Sustained response#	Type	Time to full response	Sustained response#
Synchronous Generator (incl. pumped hydro storage and CAES)	Yes	Droop respone (for pumped hydro only in gen mode)	10-20s	Yes	Droop Response*	2s	Yes
Load	Yes (if directly connected)	Droop response	few seconds	Yes	Step	0.25-0.5s	Yes
Smart Load	No	Droop response	few seconds	Yes	Proportional to Δf or RoCoF	0.5-1s	Yes
Synchronous Conden-ser	Yes	-	-	-	-	-	-
Wind Turbine	No	Droop response	few seconds	Yes (depending on wind)	Step or proportional to Δf or RoCoF	0.5-1s	Few seconds with recovery. Ineffective at low wind speed.
Solar PV	No	Droop response	few seconds	Yes (depending on sun)	Step or proportional to Δf or RoCoF	0.5-1s	Yes (depending on sun)
Battery Storage	No	Droop response	few seconds	Yes (depending on SoC)	Step or proportional to Δf or RoCoF	0.2-1s	Yes (depending on SoC)
Supercapacitor	No	-	-	-	Step or proportional to Δf or RoCoF	<0.2s	Only a few seconds (depends on size)
Flywheel	Yes (if directly connected)	Droop response	few seconds	Yes	Step or proportional to Δf or RoCoF	<0.01s	<15 min
Pumped Storage w. variable speed	No	Droop response	10-20s	Yes	-	-	-
HVDC VSC	No	Droop response	few seconds	Yes	Step or proportional to Δf or RoCoF	0.2 – 1s	No, depends on available energy

* EirGrid and SONI procure FFR with a response time of two seconds from synchronous machines, full response of FCR from these machines is expected at 5 seconds (faster than most utilites require), thus availability of FFR from synchronous machines will depend upon existing capabilities and FFR definition

Note, curtailment of renewable resource will allow sustatined response depending on primary energy source variations(e.g. sun, wind).

Source: CIGRE JWG C2/C4.41 Technical Brochure: Impact of High Penetration of Inverter-based Generation on System Inertia of Networks

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Contact Our Team

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