ESIG Webinar

Approaching Inertia and Frequency Performance in High IBR Penetration Systems

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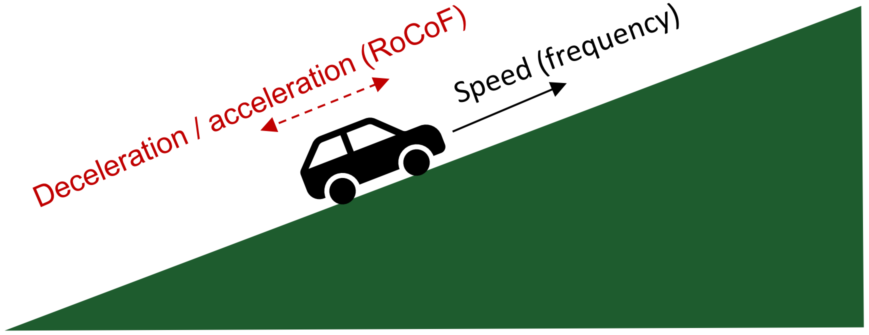
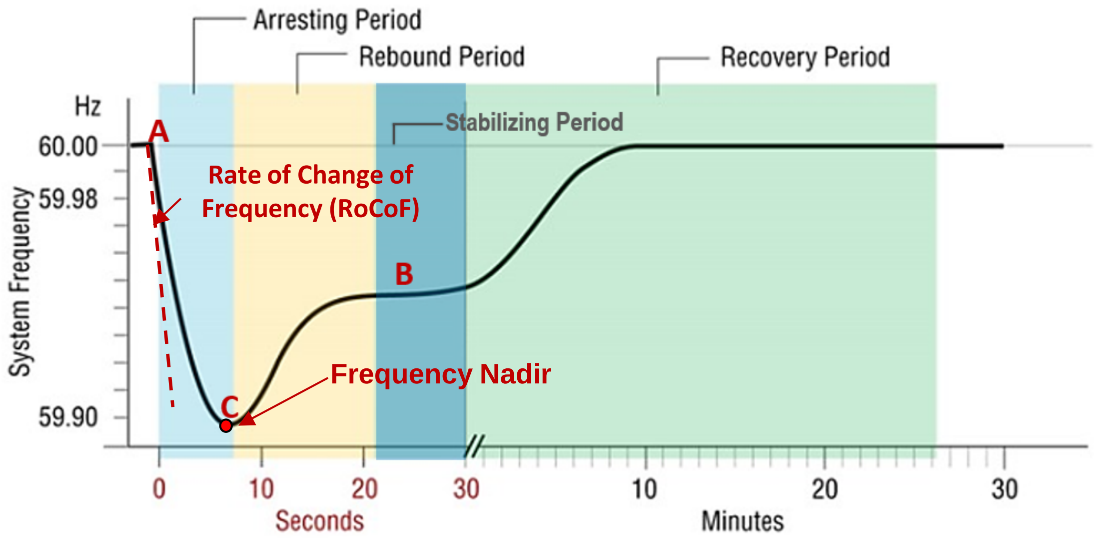
Frequency Dynamic Basics



Vehicle's responses to the deceleration:

 **Inertia due to the Vehicle Mass**

 **Additional Control from the Pedal**



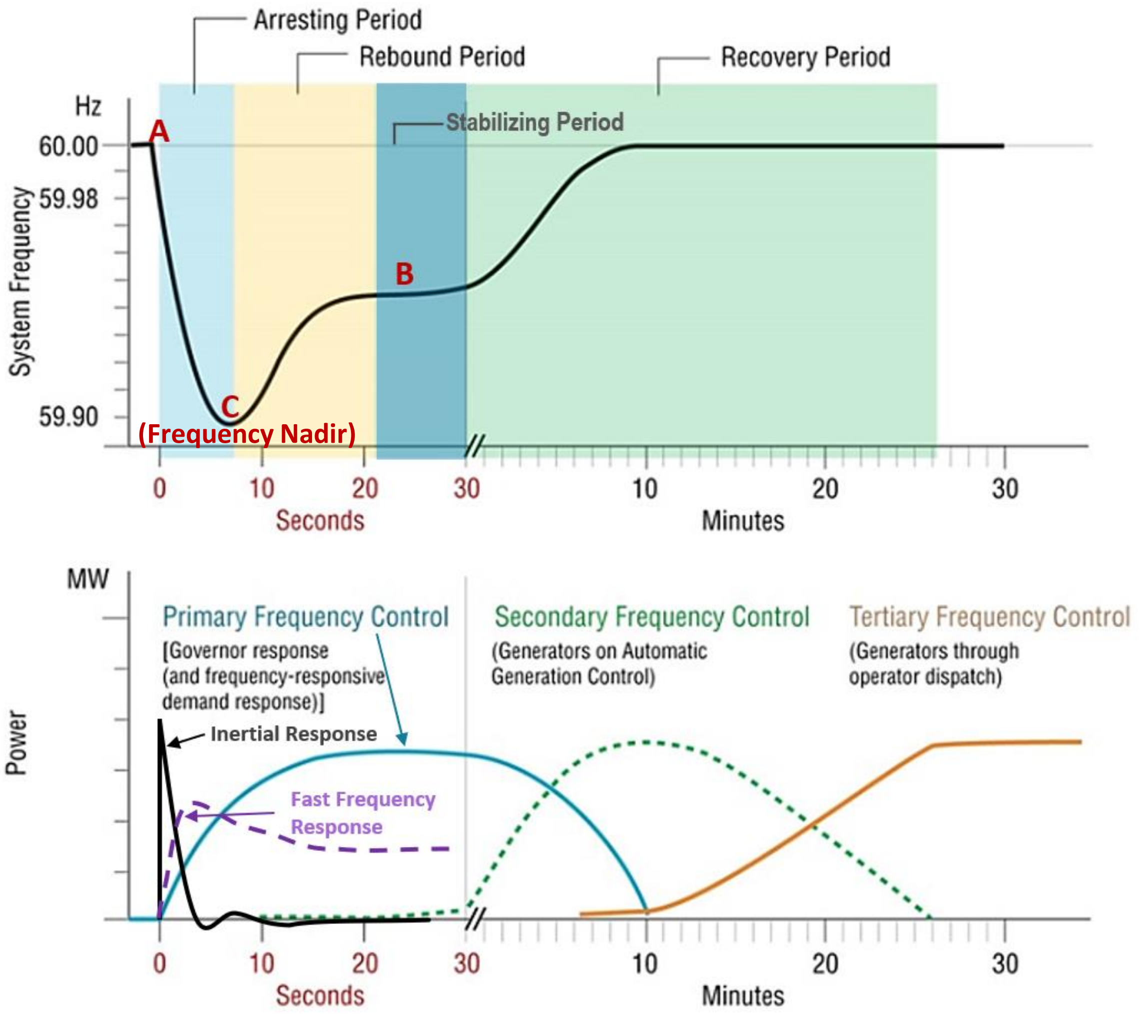
* Based on figure from [Eto, et al. Lawrence Berkeley National Laboratory, "Frequency Control Requirements for Reliable Interconnection Frequency Response", February 2018]

- **Responses to Frequency Disturbances**

 **<u>Inertial Energy</u>:** inertia from the rotating masses in generators **resists changes in frequency** (in car metaphor, the inertia of the car resists speed change), but **does not stop the deceleration**.

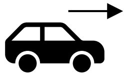
 **<u>Frequency Control Responses</u>**: various control actions to help arrest the frequency decline (**fast/primary frequency control**), recover the frequency to 60 Hz (**secondary frequency control**), and subsequent control actions to optimize the power flow.

Frequency Dynamic Basics



* This is **<u>an edited figure</u>** based on reference [Eto, et al. Lawrence Berkeley National Laboratory, “Frequency Control Requirements for Reliable Interconnection Frequency Response”, February 2018]

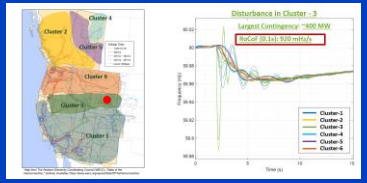
***** Curves are for demonstration of the time frames of different responses only. Shapes of the actual responses depend on system characteristics and controls.***

- **Inertial Energy Injection** 
  - Instant support due to extraction of kinetic energy from rotating masses.
- **Fast Frequency Control** 
  - Faster than conventional generator governors but slower than physical inertia.
  - Enabled by IBR controls or fast load shedding schemes
- **Primary Frequency Control** 
  - Automatic governor response of generating units and load response from frequency-sensitive loads.
  - Stabilizes the frequency at a new level, but does not recover it to the nominal operating frequency.
- **Secondary Frequency Control** 
  - Restores the frequency to the nominal value through automatic generation control (AGC) or manual dispatch.
- **Tertiary Frequency Control** 
  - Restores the reserves used for secondary frequency control and controls the power exchange on inter-ties.

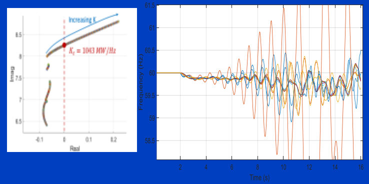
Overview

Inertia Regionalization and Frequency Response

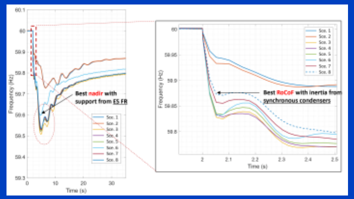
1 Inertia Regionalization and Local Frequency Dynamics



2 Frequency Response Deliverability Screening



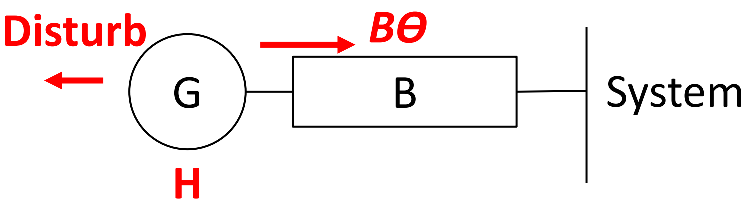
3 Bulk System Frequency Performance Assessment and Improvement

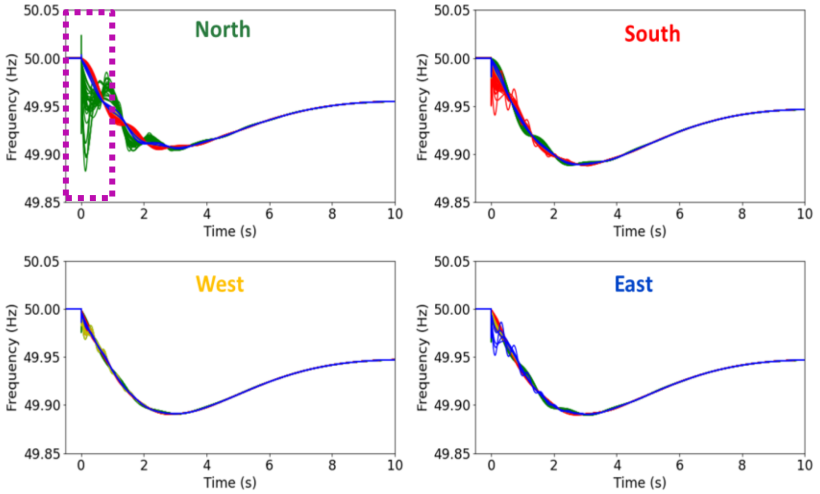


Inertia Regionalization and local Frequency Dynamics

Reference: EPRI Technical Report, "Inertia Estimation and Monitoring: Algorithm and Case Studies"

Regional Aspect of Frequency Dynamics





Example – regional frequency dynamics in the Great Britain system

Inertial frequency response of the system is governed by:

$$2\boldsymbol{H}\frac{dw}{dt} = Pm - \boldsymbol{B}\theta$$

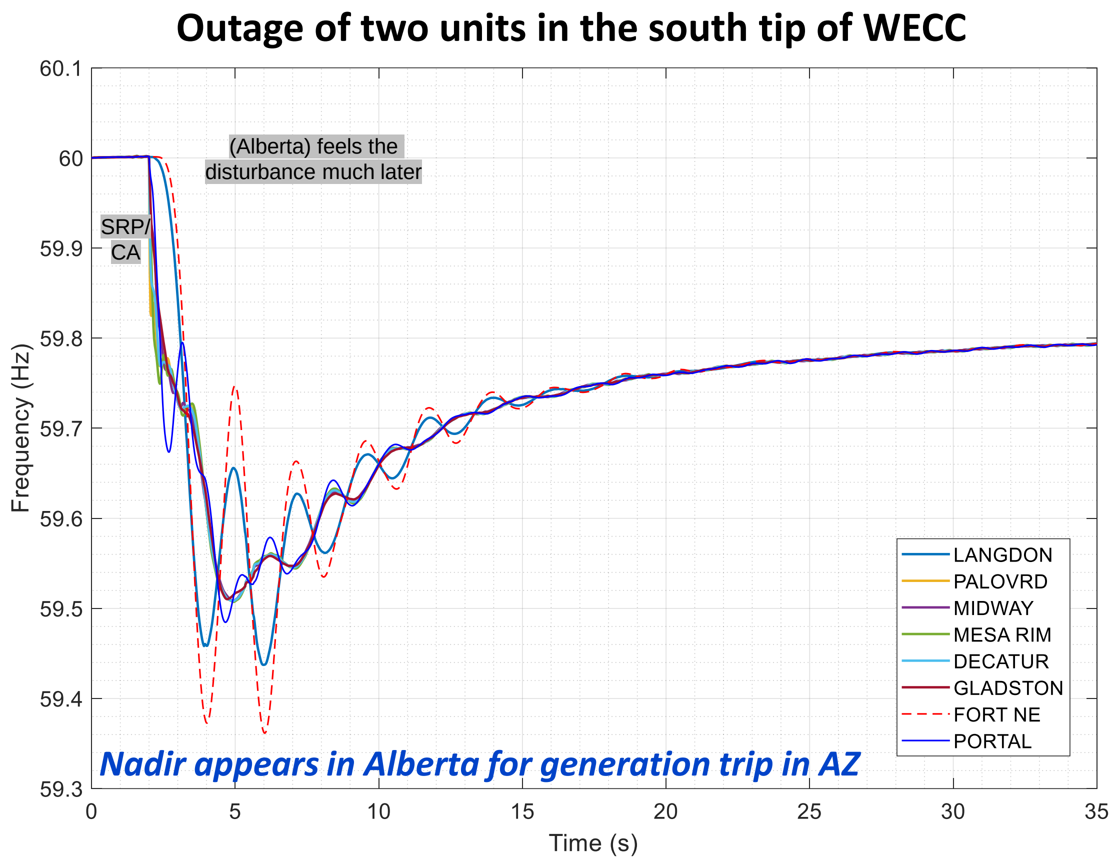
Inertia — Connection Strength

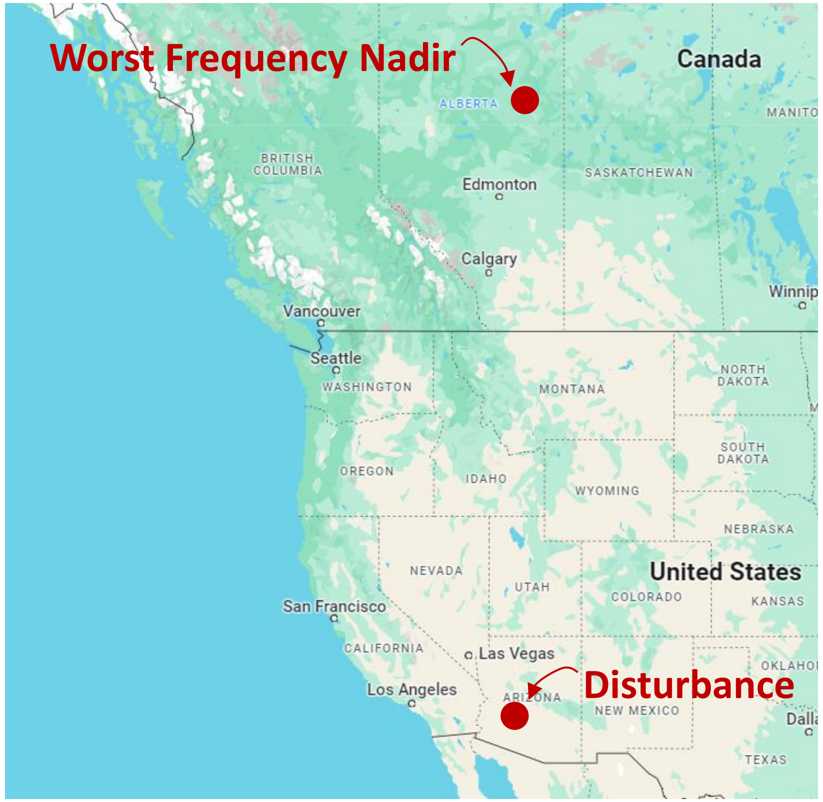
- ✓ **H** represents the inertia that resists frequency declines (limits RoCoF)
- ✓ **B** determines how much of a **stabilizing/synchronizing effect the neighboring systems provide**
- ✓ If H and B are both high generators move **fairly in unison**
- ✓ If **H and/or B were to decrease considerably in specific regions**, the regions will become ***nimble and loosely coupled***

- ➢ Integration of more IBRs **decreases *H*** and **increases the risk of regional inertia issues**.
- ➢ Traditional interconnection-wide frequency studies may overlook these regional frequency dynamics – **regionalization of the inertia** helps **identify risky areas** and **informs necessary mitigation measures**.

Regional Aspect of Frequency Dynamics

➢ **Simulation results from an EPRI-SRP inertia and frequency study project**





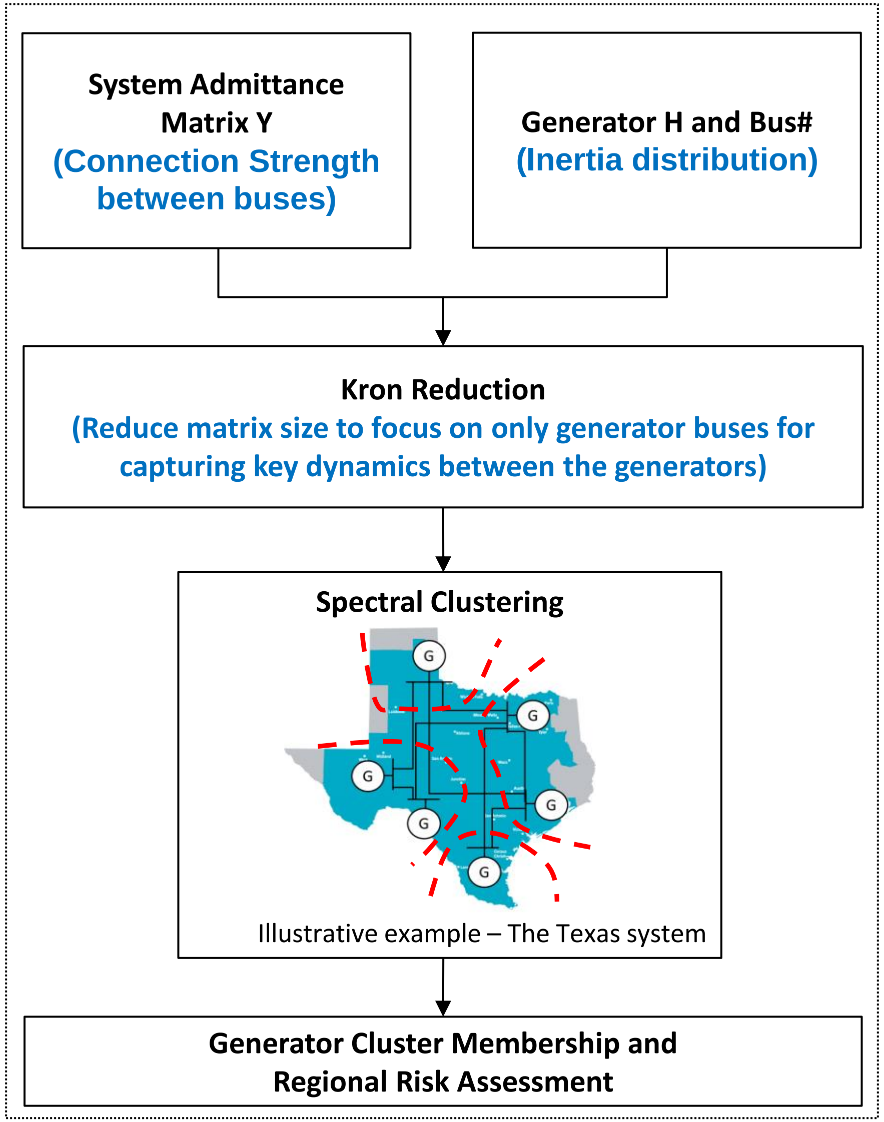
- **Frequency dynamics in certain regions** can deviate from the rest of the system due to their **regional inertia levels** and their **weak connections** to the rest of the system.
- More details will be discussed later in the presentation about the inertia regionalization analysis.

Inertia Regionalization and Risk Identification

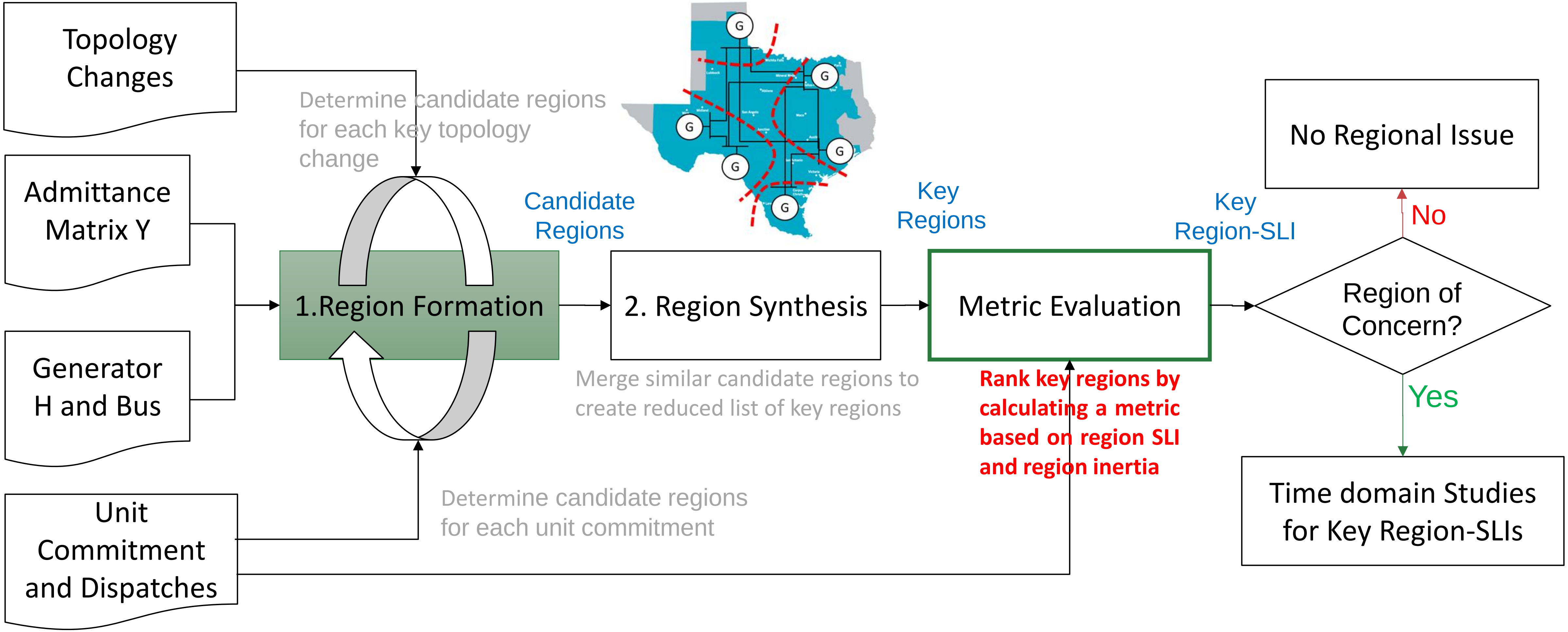
- Integration of more IBRs **decreases *H*** and **increases the risk of regional inertia issues**.
- Traditional interconnection-wide frequency studies may overlook these regional frequency dynamics – **regionalization of the inertia** helps **identify risky areas** and **informs necessary mitigation measures**.

- A **spectral clustering approach** is used to group generators based on basic system information.
- **Inputs**
  - ✓ **Basic Network Data** (Connection strength between generators)
  - ✓ **Generator dispatch and inertia constants** (distribution of inertia)
- **Outputs**
  - ✓ **Clustering** results of generators
  - ✓ Metrics for **identifying risky regions**

**Does not require time-domain simulations*



Inertia Regionalization and Risk Identification

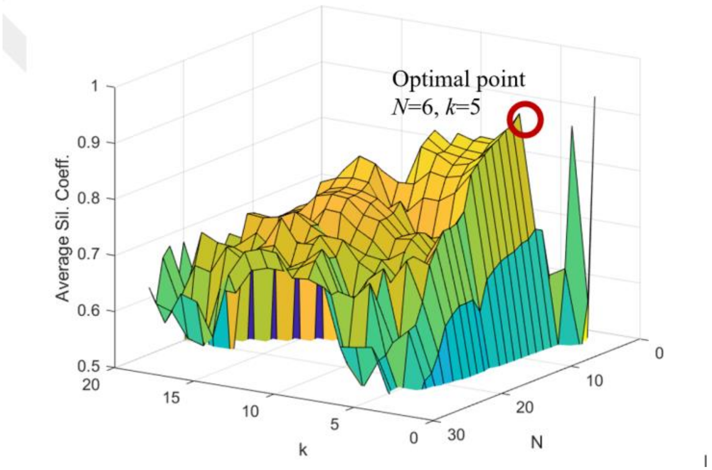


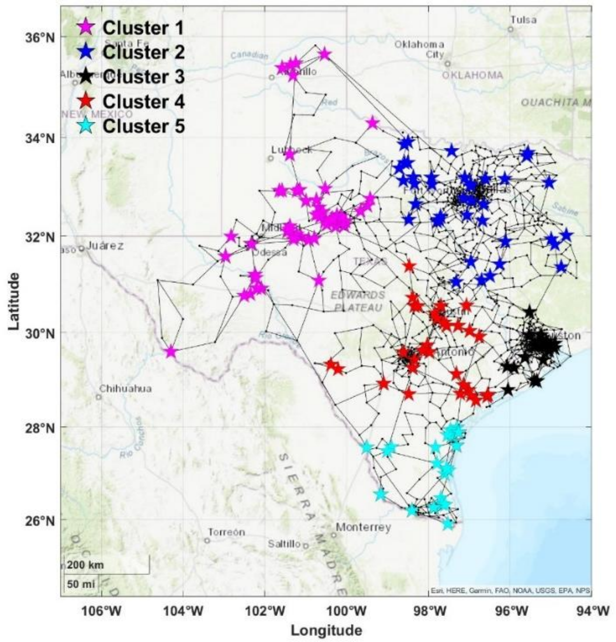
This algorithm has been demonstrated on the Synthetic Texas system with satisfactory outcome

Application example: Synthetic Texas System

- The framework was tested on the synthetic Texas system available through Texas A&M university
- Identified 5 optimal clusters
- Regional Inertia, Single Largest Infeed loss, and regional inertia risk metric are identified for each region and TDS was performed.

Region	5	1	2	3	4
Region Inertia (GWs)	244	859	118	585	591
R-SLI (MW)	1144	1351	209	1212	552

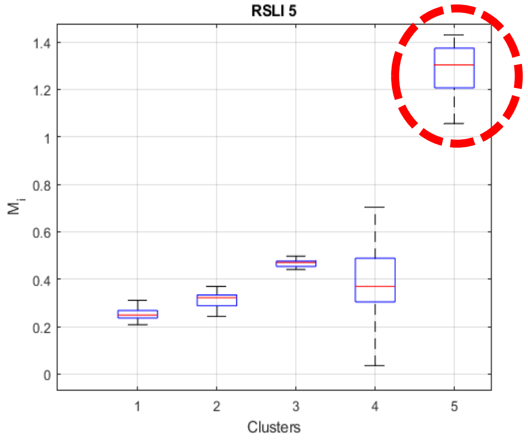


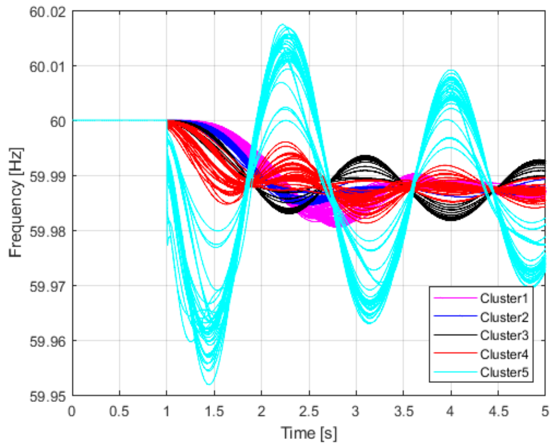


Metric for 'Risk of Low Inertia' determination

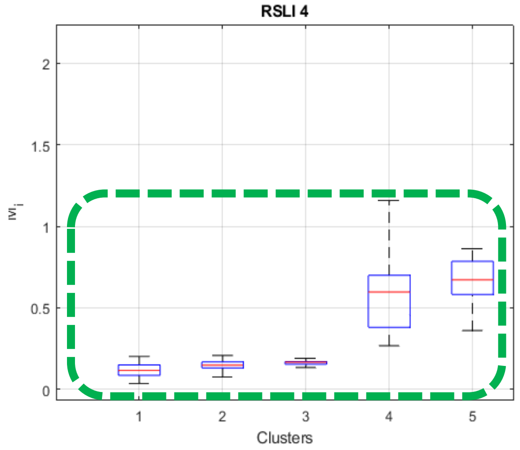
- A metric M has been developed, that can be calculated numerically without solving a detail TDS.
- Metric approximately identifies if certain clusters can exhibit low inertia issues.
- The further the M metric box plot of a region deviates from other regions, the higher the risk of that region to experience high RoCoF levels and regional frequency dynamics

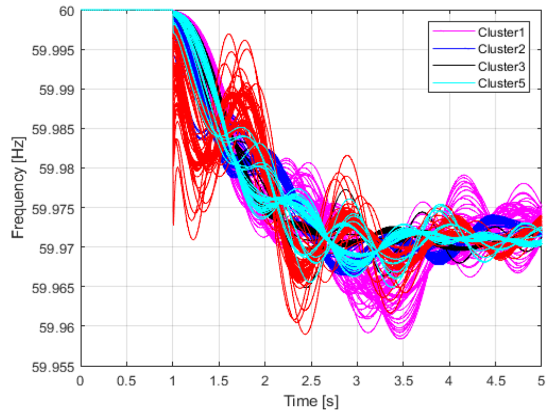
Fast evaluation of the metric enables easy sensitivity assessment





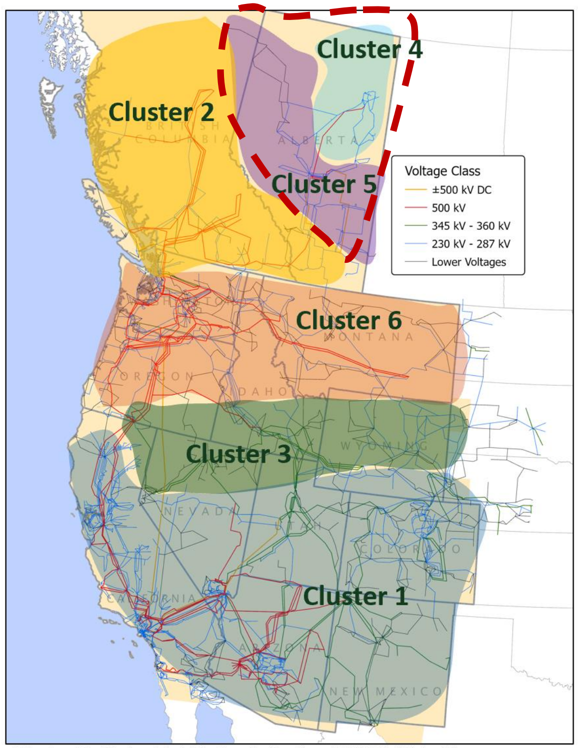
Area 5 'M' values is high and separated from 'M' values of other areas. Possibility of 'regional inertia issue' in region 5



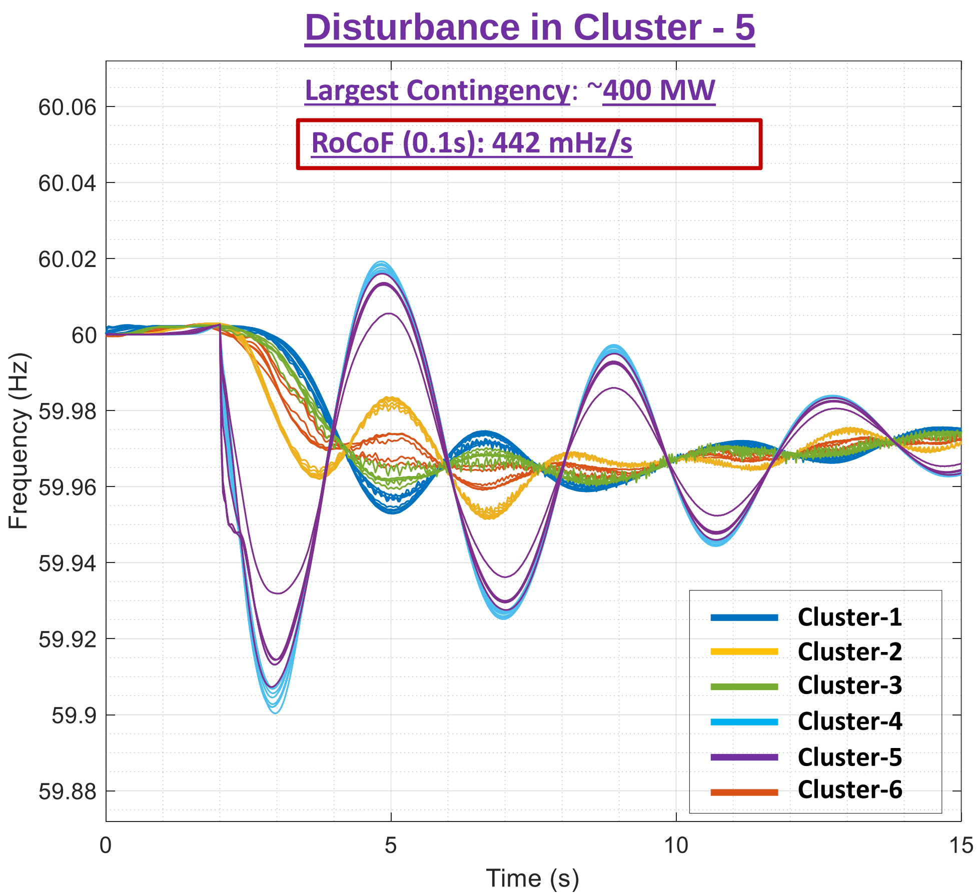


'M' values are clustered together showing region 4 is well connected to the remaining system

Application Example: EPRI-SRP Inertia/Frequency Project

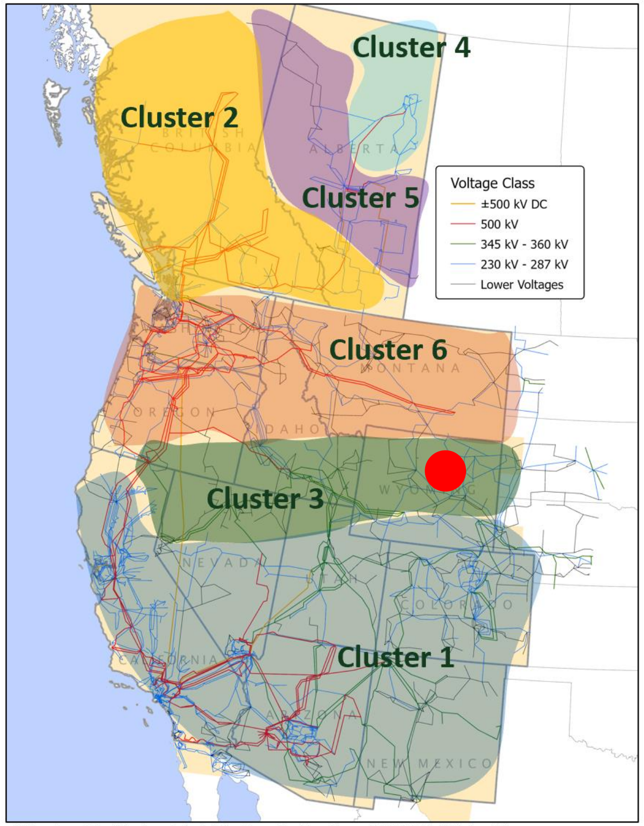


*Map from The Western Electricity Coordinating Council (WECC), "State of the Interconnection," [online]. Available: https://www.wecc.org/epubs/StateOfTheInterconnection



- The largest RoCoF measured for in Cluster 5 is **442 mHz/s** despite a small 'largest contingency' of only 400MW.
- This cluster is located on the northern end of WECC with sparse transmission lines network (**weak connection**) and a small generation fleet (**low regional inertia**) . This resulted in **high RoCoF levels** and **oscillatory behaviors** as it sits at the end of the network.

Application Example: EPRI-SRP Inertia/Frequency Project



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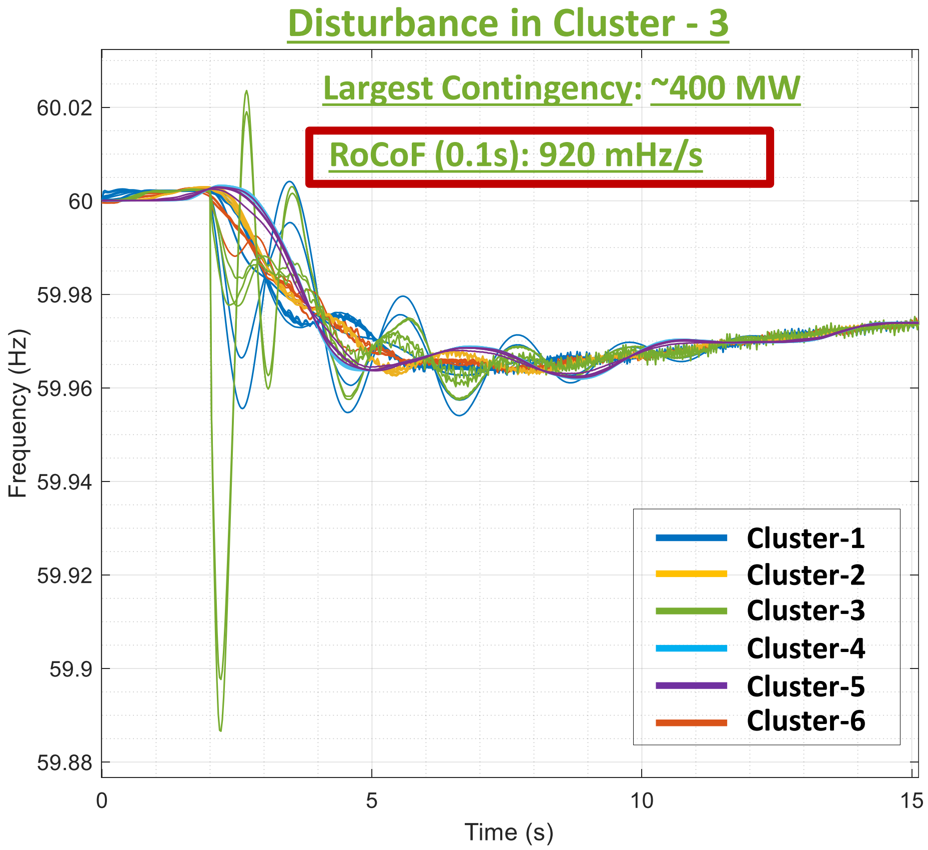
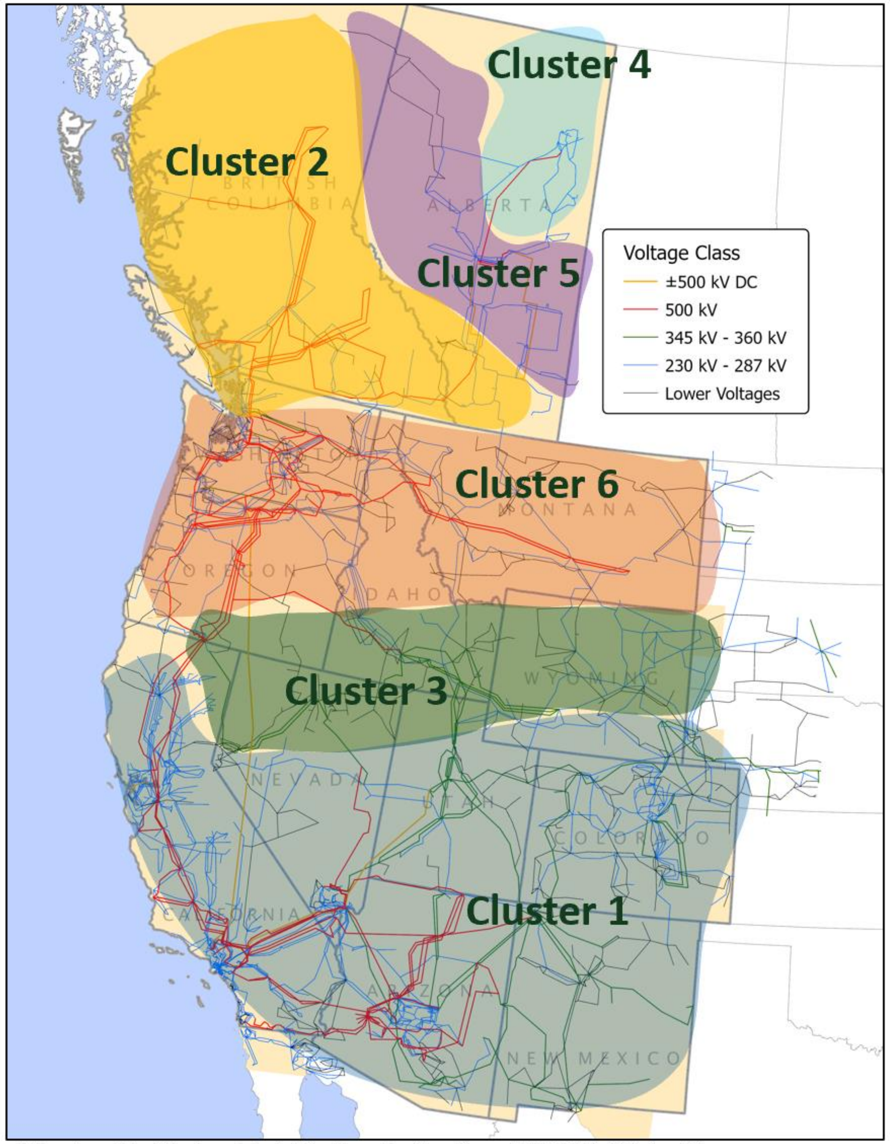


- The largest RoCoF is measured in **East Wyoming** at **920 mHz/s**.
- The smaller generation fleet (**low regional inertia**) and sparse high voltage transmission network (**weak connection strength**) resulted in **high RoCoF levels** even with a small generation trip event of 420 MW.

Application Example: EPRI-SRP Inertia/Frequency Project



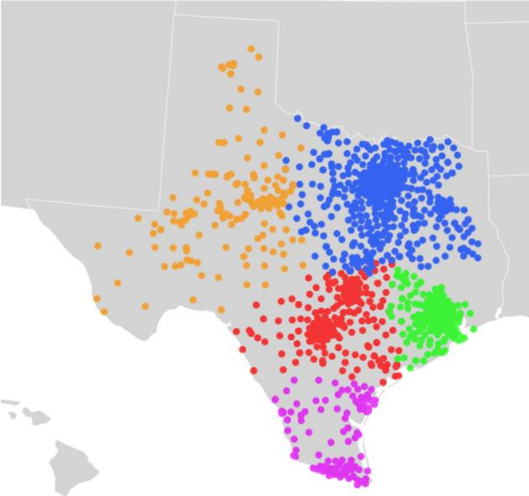
*Map from The Western Electricity Coordinating Council (WECC), "State of the Interconnection," [online]. Available: https://www.wecc.org/epubs/StateOfTheInterconnection

Inertia Regionalization Key Takeaways:

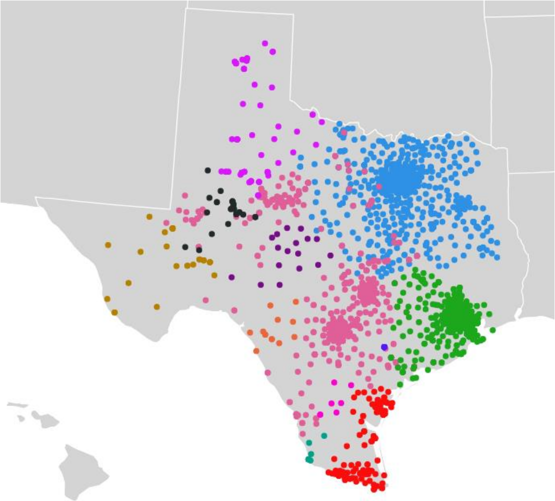
- As inertia is usually not distributed evenly across the system, most interconnections can expect to experience **regional inertia issues before interconnection-level inertia insufficiency**.
- This can be further aggravated by the **increasing integration of IBRs**.
- The inertia regionalization study helps **expedite the screening** for areas at high risk of regional inertia issues, which could be **otherwise difficult to identify through interconnection-wide frequency studies**.
- System operators and planners are encouraged to pay attention to **regions identified with high risks** and conduct **further detailed studies** to ensure satisfactory frequency performance in the regions.
- Periodical inertia regionalization studies are encouraged as the inertia distribution could change as system generation mix evolves.

Multi-Perspective Remedial Action for Regionalized Issues

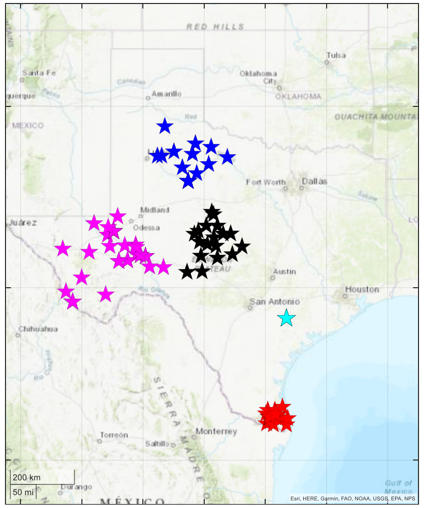
- Bus/Generator clustering methods are utilized in **inertia**, **voltage**, and **grid strength** analyses.
- They are based on either **admittance-matrix-based spectral clustering** or **sensitivity analyses**.
- Overlaying multiple clustering results from these aspects has the potential to **identify locations for optimal remedial decisions** that take **all these perspectives** into consideration.
- This leads to most **efficient remedial actions** that attend to all aspects and **avoids deterioration** in other aspects when placing resources for a certain purpose.



Inertia Regionalization



Voltage Control Area Tool



Grid Strength Assessment Tool

Inertia Regionalization: Identify inertia clusters and assess regional inertia risks. Link to EPRI Technical Report.
Voltage Control Area (VCA) Tool: Determine voltage control areas and assessment of reactive power reserve for transmission systems. Link to VCA Tool.
Grid Strength Analysis Tool (GSAT): Evaluate system strength under various network and topology conditions. Link to GSAT.

Questions? Feel free to contact us to know more about these EPRI tools. Deepak Ramasubramanian (dramasubramanian@epri.com); Parag Mitra (pmitra@epri.com); Chengwen Zhang (czhang@epri.com); Vikas Singhvi (vsinghvi@epri.com);

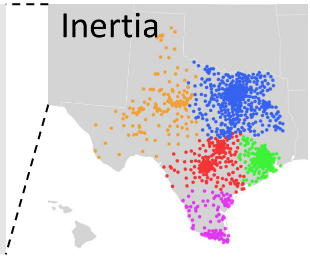
Inertia Regionalization

VCA Regionalization

GSAT Weak Spot Identification

Region Partitions

- RoCoF
- Frequency Nadir
- Frequency response delivery



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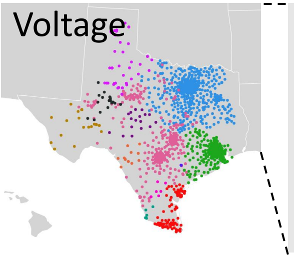
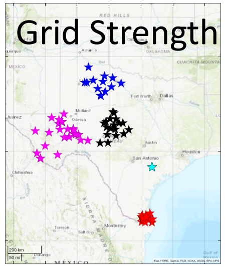


- Voltage Limits
- Max. Volt. Deviation
- Generator PF
- Transformer taps

Weak Spots



Overlaps:

1. Areas with potential for shared resource siting for <u>**both inertia and voltage purposes**</u>. (**Co-Treatment Areas**)
2. **Flexibility** in siting of the resources within coherent areas.

Disparities:

1. Areas where inertia and voltage coherences do not agree. (**Dedicated Areas**)
2. Identification of potential <u>**critical buses**</u> is recommended after the addition of co-treatment resources in overlap areas.

GS Weak Spots:

1. **Spots to avoid when siting IBR**-based resources for inertia/VCA purposes.
2. **Sync. Condensers/generators prioritized** when strengthening these spots is desired.
3. **Ride-through capability studies required** for IBRs/STATCOMs in weak spot areas.

Potential <u>**Areas**</u> **&** <u>**Resource Types**</u> for remedial actions

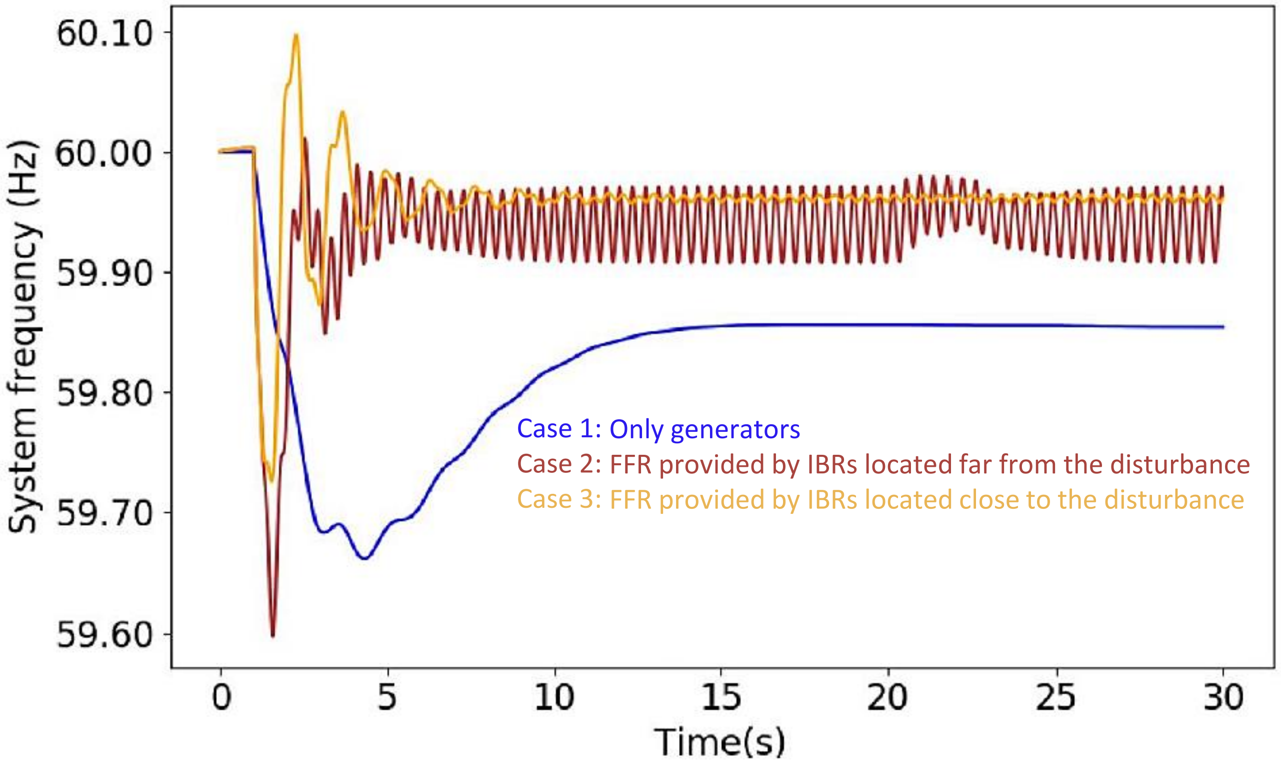
<u>**Spots**</u> & <u>**Resource Type**</u> suggestions

Resource type, Siting, and Sizing Co-Optimization for <u>Inertia</u>, <u>Voltage</u>, and <u>Grid Strength</u>

Frequency Response Deliverability

Reference: EPRI Technical Report, "Bulk System Frequency Performance and Assessment Under High Levels of Variable Generation: Deliverability of Primary Frequency Response and Regionalization for Frequency, Voltage and Grid-Strength

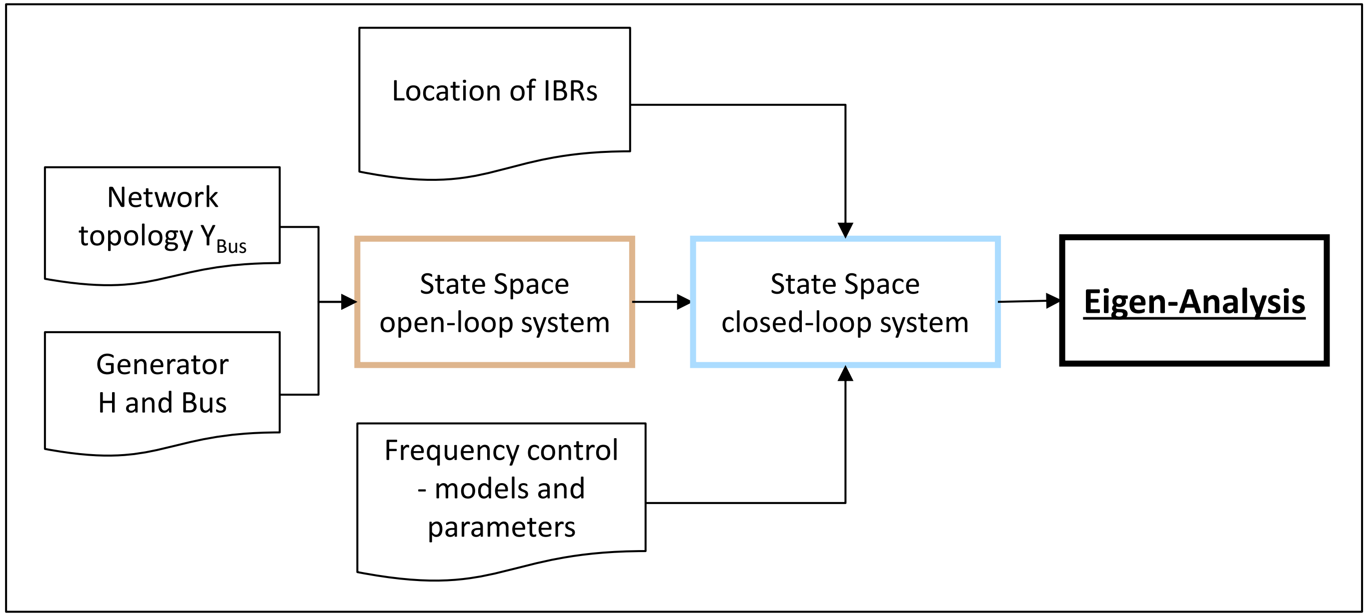
Locational Aspect of Fast Frequency Reserves



- How do we rapidly screen instability scenarios with IBR FFR at specific locations to further identify the need for, and inform the conduction of, time-domain simulations?
- How do we optimally allocate IBR FFR among multiple resources for better disturbance rejection performance?

Rapid Screening of Fast Frequency Response Stability Issues

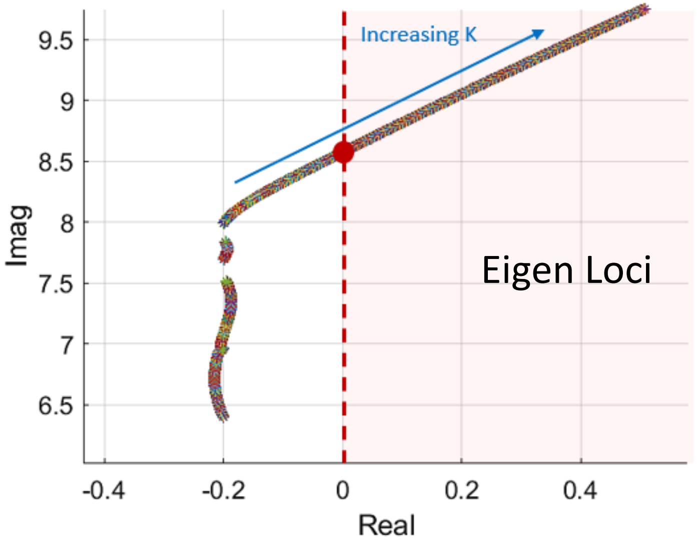
- For specific IBR locations, how can we quickly screen them for stability issues?
- **Factors** that determine stability characteristics include **location** of the IBRs, **regional inertia**, **area connection strength**, and **response characteristics** of the FFR resources.
- Using Eigen-Analysis on the approximate state matrix has the benefit of rapid calculation to capture the key dynamics FFR resources bring to the system.
- This identifies the need for, and inform the conduction of, further detailed time-domain simulation studies.



Open-loop State Matrix | FFR Resources

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{P}_u \\ \Delta\dot{u} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\frac{L}{M} & -\frac{D}{M} & \frac{1}{M} & 0 \\ 0 & 0 & -\frac{1}{T_c} & \frac{1}{T_c} \\ \frac{KT_A}{T_B}\left(-\frac{L}{M}\right) & \frac{KT_A}{T_B}\left(-\frac{D}{M}\right)+\frac{K}{T_B} & \frac{KT_A}{T_B}\left(\frac{1}{M}\right) & -\frac{1}{T_B} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta P_u \\ \Delta u \end{bmatrix}$$

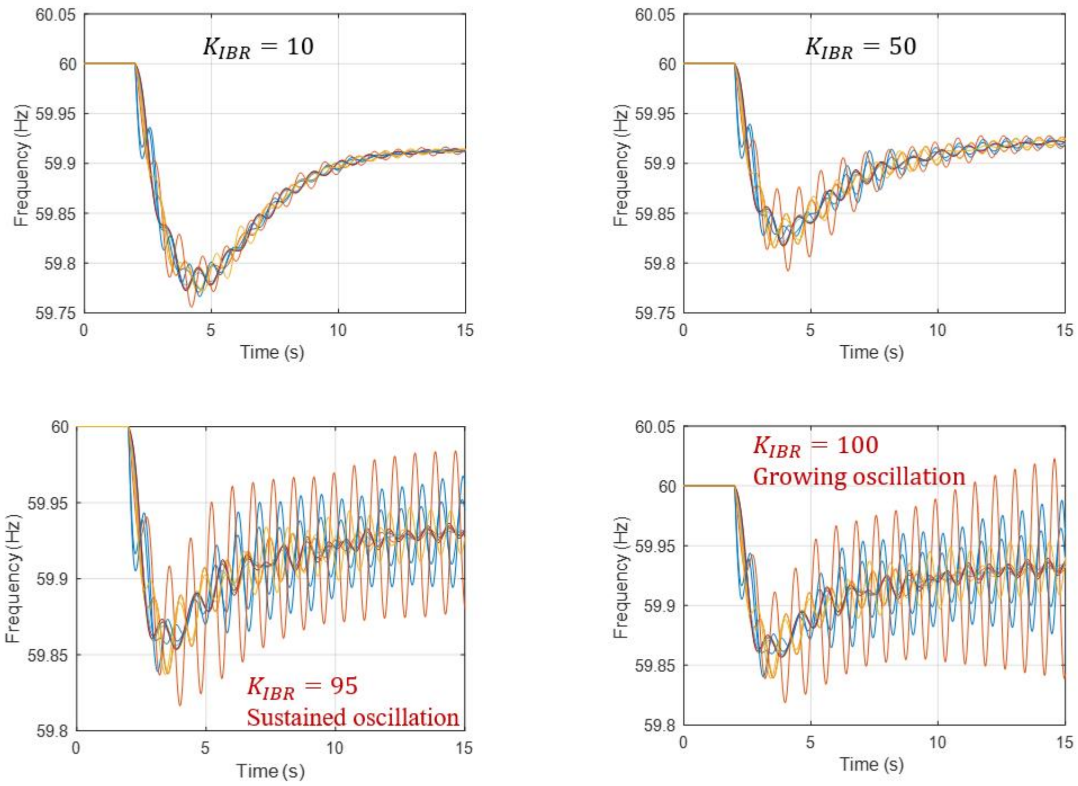
Rapid Screening Example: Droop Scan



Critical Gain: $K_{IBR} = 97.68$

Oscillation Frequency: $f_{osc} = \frac{8.51}{2*pi} = 1.35\ Hz$

Time Domain Simulations



- Predicted instability when IBR **droop gain** goes over 95.
- Predicted the oscillation frequency to be **1.35 Hz**, close to the **1.30Hz** oscillation in time-domain simulation.
- **This formulation does not capture all dynamics of the system due to its simplified modeling of the system (capturing only electromechanical interactions). Study is undergoing for developing metrics/indices out of this formulation for indicating risk of instabilities. The goal is to expedite the stability screening and inform further detailed time-domain simulation studies.**

Rapid Screening of Fast Frequency Response Stability Issues

- Regional Inertia
- Connection Strength
- IBR FR Characteristics

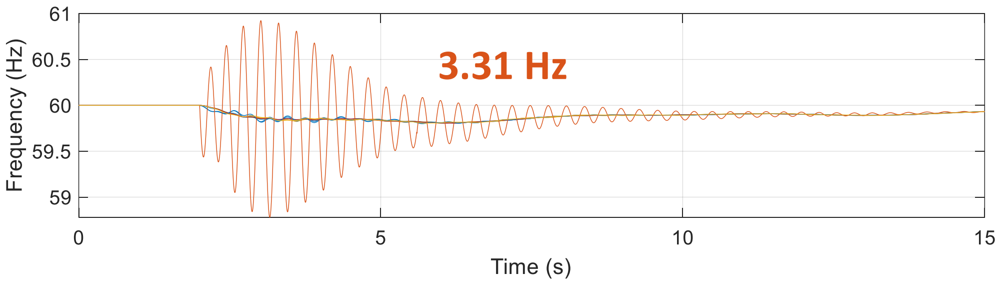
Local Oscillations
Interactions between the IBR FR and local rotating mass

Inter-area Oscillations
IBR FR participating in potential inter-area modes

Electromechanical oscillations

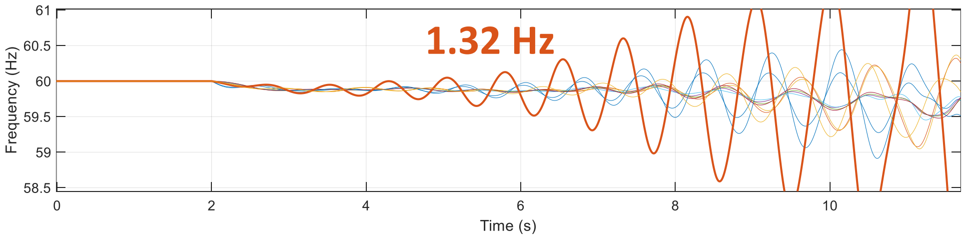
Type 1:

Low-inertia, weakly-connected region + High IBR Droop Gain
→ Local Generator-IBR FR oscillations



Type 2:

Intermediate/high inertia region + High IBR Droop Gain
→ Potential Inter-area oscillations



Addressing Utility-Specific Inertia and Frequency Response Challenges

EPRI – SRP Inertia/Frequency Study

Background

- SRP (Salt River Project) is a community-based, not-for-profit organization providing reliable, affordable and sustainable water and energy to more than 2 million people in central Arizona.

Delivering water and power™

- **SRP Transmission IBR Integration Journey**
  - Pre-2023: 420MW of Solar/35MW of BESS
  - End of 2023: 768MW of Solar/483MW of BESS
  - End of 2024: 1268MW of Solar/1123MW of BESS/160MW of Wind
  - **More coming in 2025!**

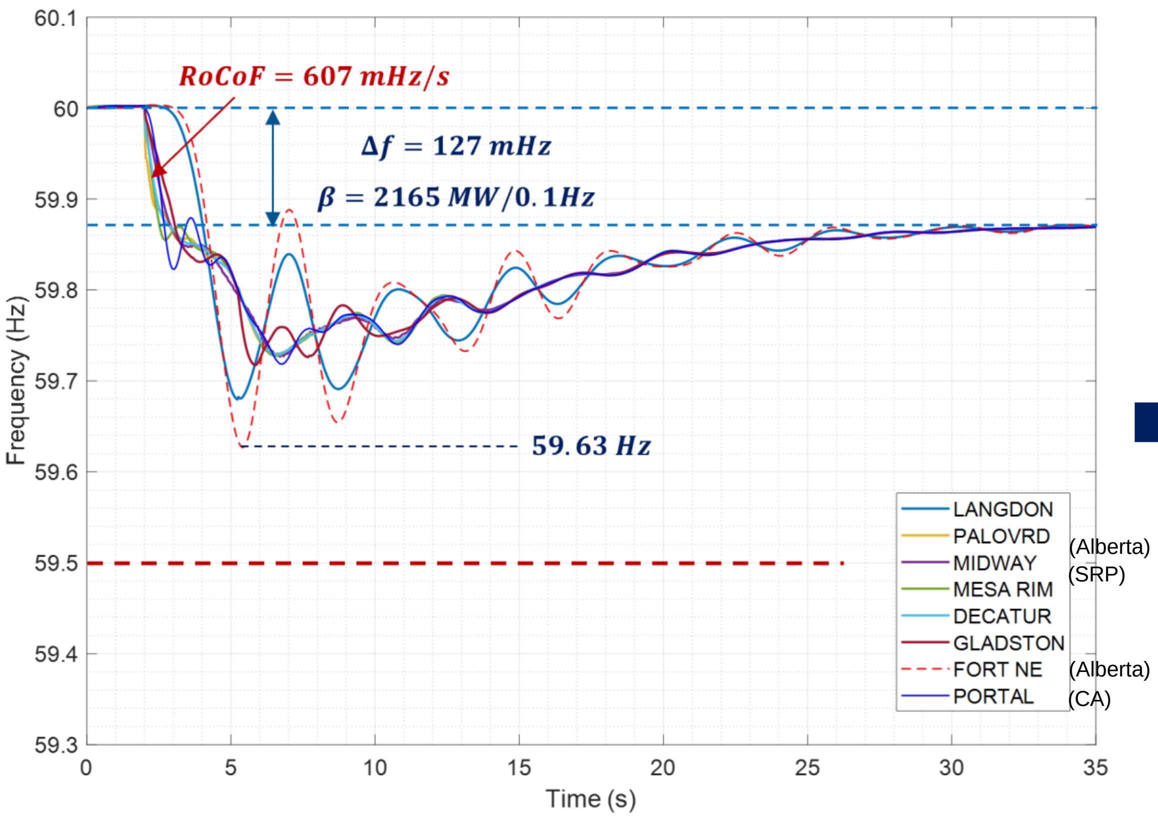
SRP Frequency Study Background

➢ Background and Motivation for SRP Frequency Study

- Even though SRP's system is geographically very tight and robust serving the Phoenix Metropolitan area and therefore expected not to see significant frequency issues with the addition of over 2500MW of IBRs over the next few years, this is still a large gap in SRP knowledge that deserves attention for due diligence to our customers and our participation in the wider western interconnection.
  - To assess the increasing **IBR integration's impact** on frequency performance in SRP and WECC.
  - To understand **how IBRs can be used for fast frequency support**
  - To **compare the performance of different resources** in providing frequency support
  - To identify areas at high risk of regionalized frequency dynamics and inertia issues

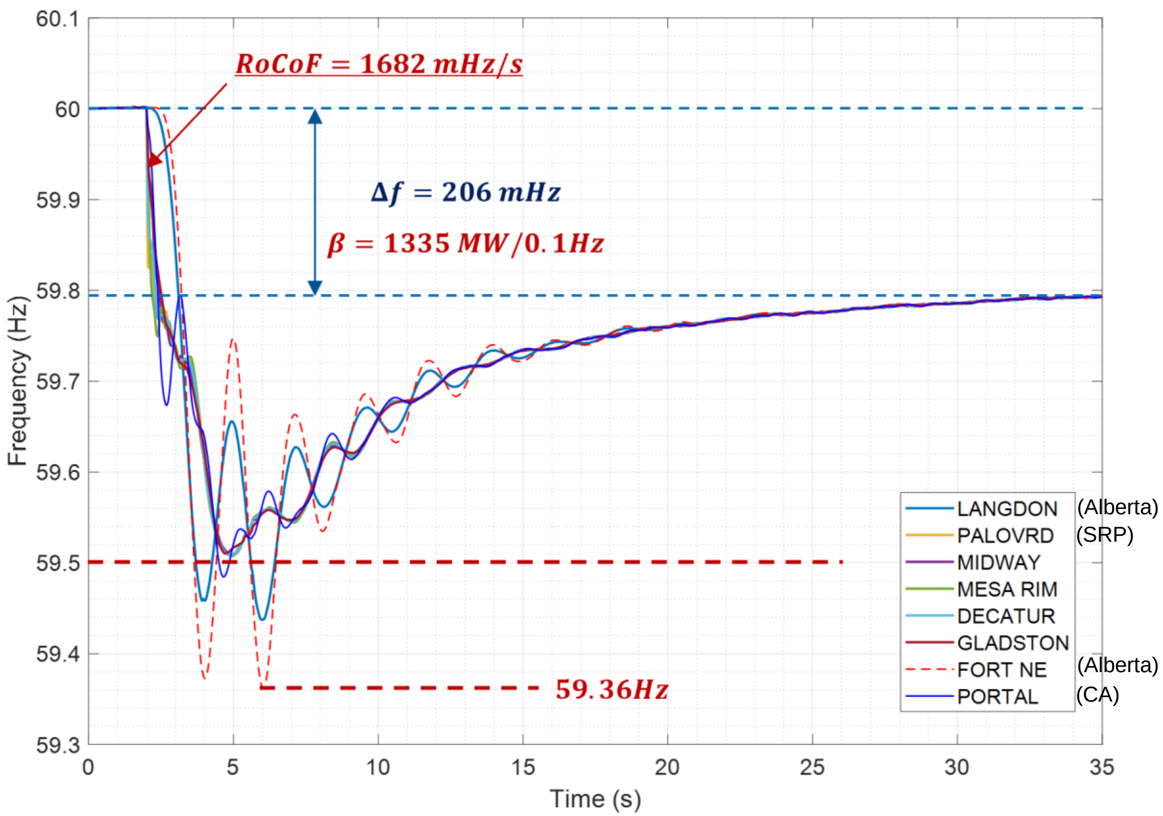
Impact of IBR Integration on Frequency Performance

IBR Penetration: 17.5%



IBR Penetration: 69.6%

*High IBR Penetration across WECC



RoCoF (mHz/s):
*0.1s window, in SRP
607 → 1682

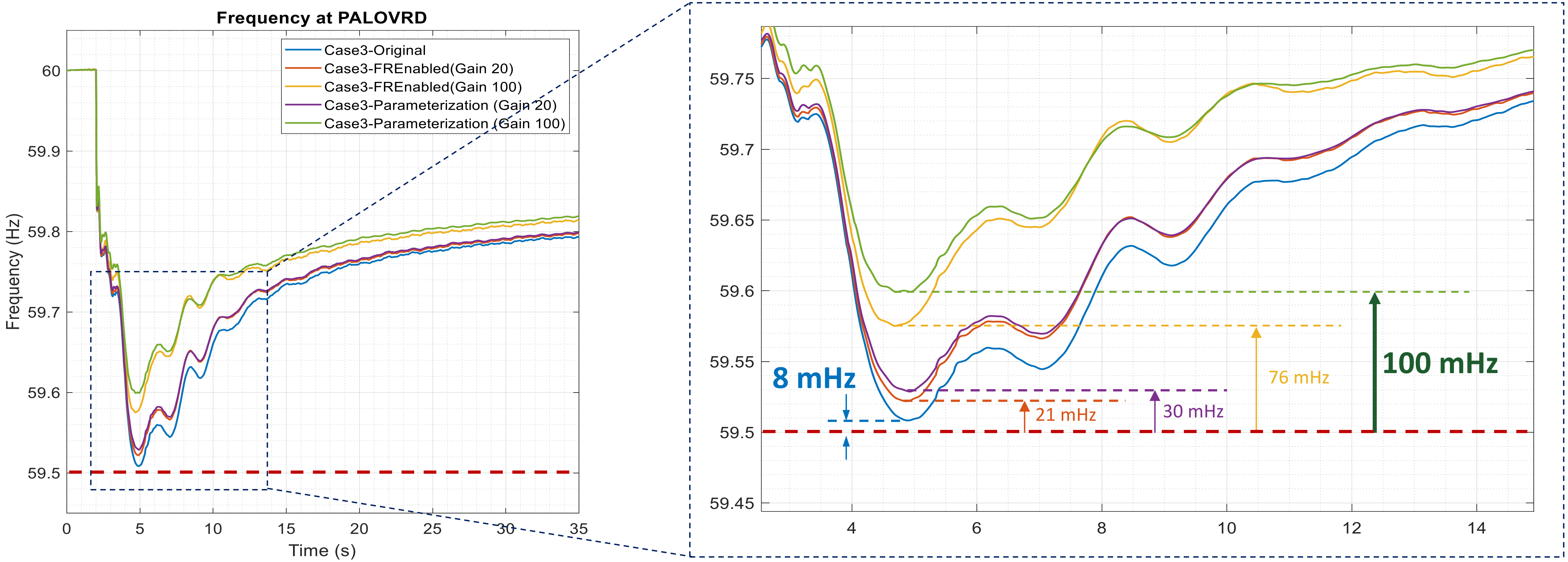
Frequency Response (MW/0.1Hz):
2165 → 1335

UFLS Margin (mHz):
*in SRP
230 → 8

Deterioration in both RoCoF and frequency nadir observed with high IBR penetration.

IBR Contribution to Frequency Support and Parameterization

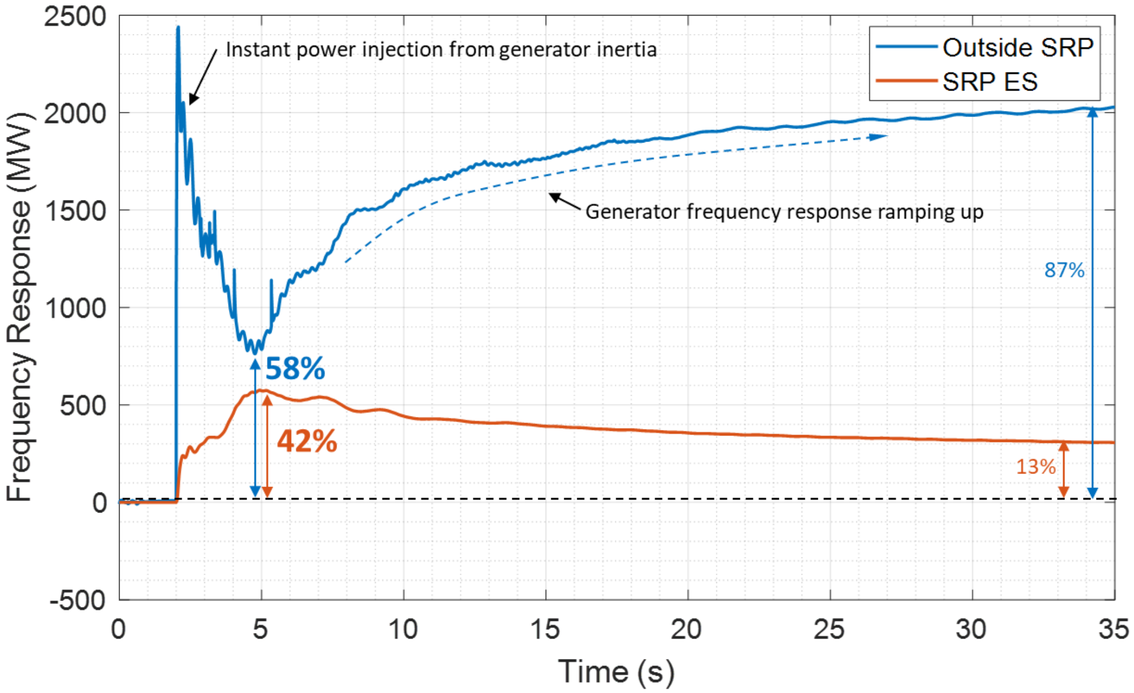
- With only energy storage IBRs within SRP area providing fast frequency response



Improvement in frequency nadir is achieved with proper parameterization of the IBR fast frequency response.

- **Without IBR frequency support: 8 mHz**
- **With IBR frequency support**
  - Before parameterization: 21 mHz
  - **After parameterization: 100 mHz**

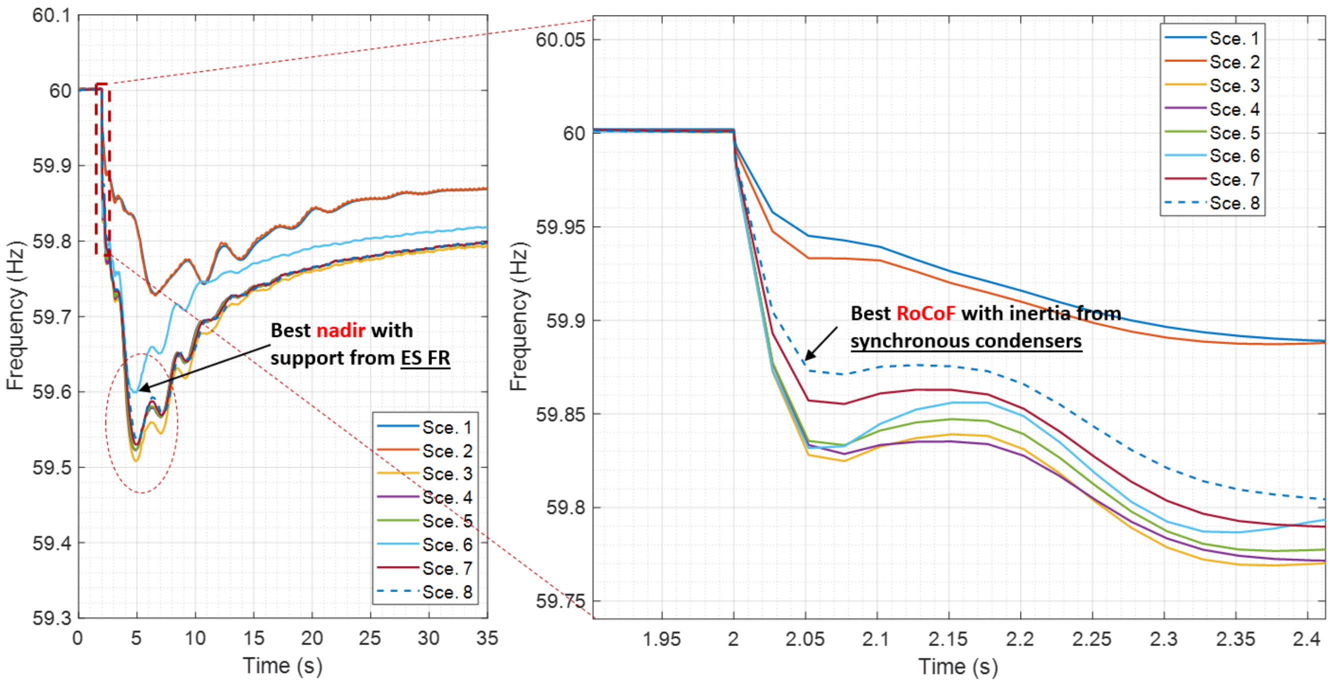
IBR Contribution to Frequency Support and Parameterization



- Headroom on the SRP energy storage IBRs is only **2.5%** of the total headroom (available in entire WECC).
- The peak contribution of these SRP IBRs reaches **42%** of the total response, quickly support the deviating frequency.
- IBR frequency response is faster than generator governor actions – the frequency responsive IBRs will take more responsibility in the early stage of the response when the generator frequency response has yet to ramp up. This fast response buys time for other slower resources to be able to ramp up and participate in frequency response.
- Note that in more realistic scenarios, as IBRs outside SRP also participate in fast frequency response, the share taken by SRP IBRs will fall to a more reasonable value and the frequency performance can be expected to further improve with an even larger pool of frequency responsive IBRs across WECC.

How Different Resources Compare to Each Other in FR Provision?

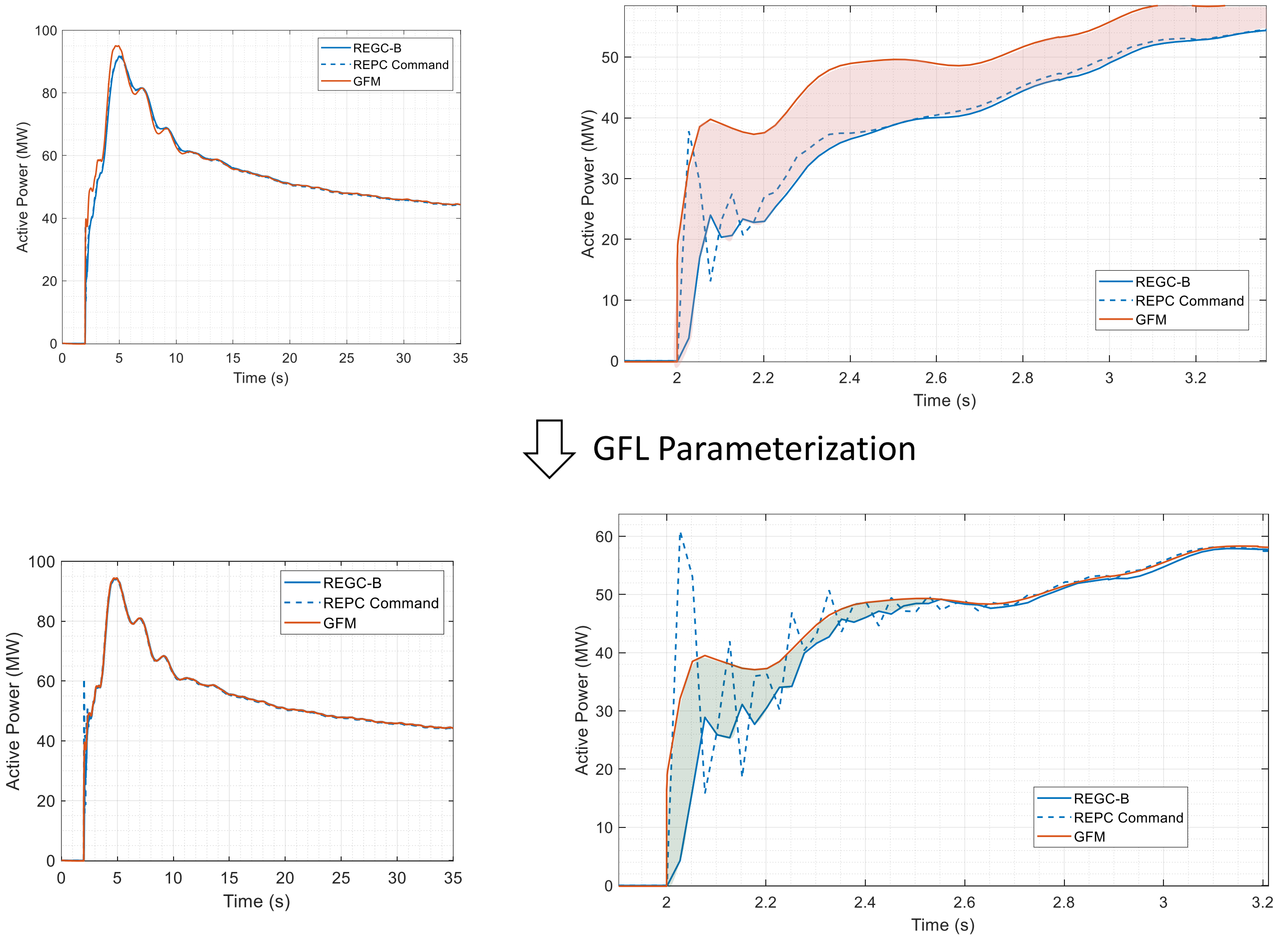
➢ **Synchronous condensers vs. IBRs**



- **Synchronous condensers** mainly help with the **RoCoF** due to the instantaneous release of inertial energy, which **does not sustain** long enough to impact **frequency nadir** significantly.
- **Energy storage IBRs** can provide **sustained response** and hence improve **frequency nadir**, but they are **not as effective** as synchronous condensers in improving **RoCoF**.
- While IBRs and synchronous condensers are compared for their performance in frequency support, this study is not a comprehensive study on technology recommendation. Future studies are encouraged to understand the services various resource can provide and a coordinated resource utilization for maximized benefits.

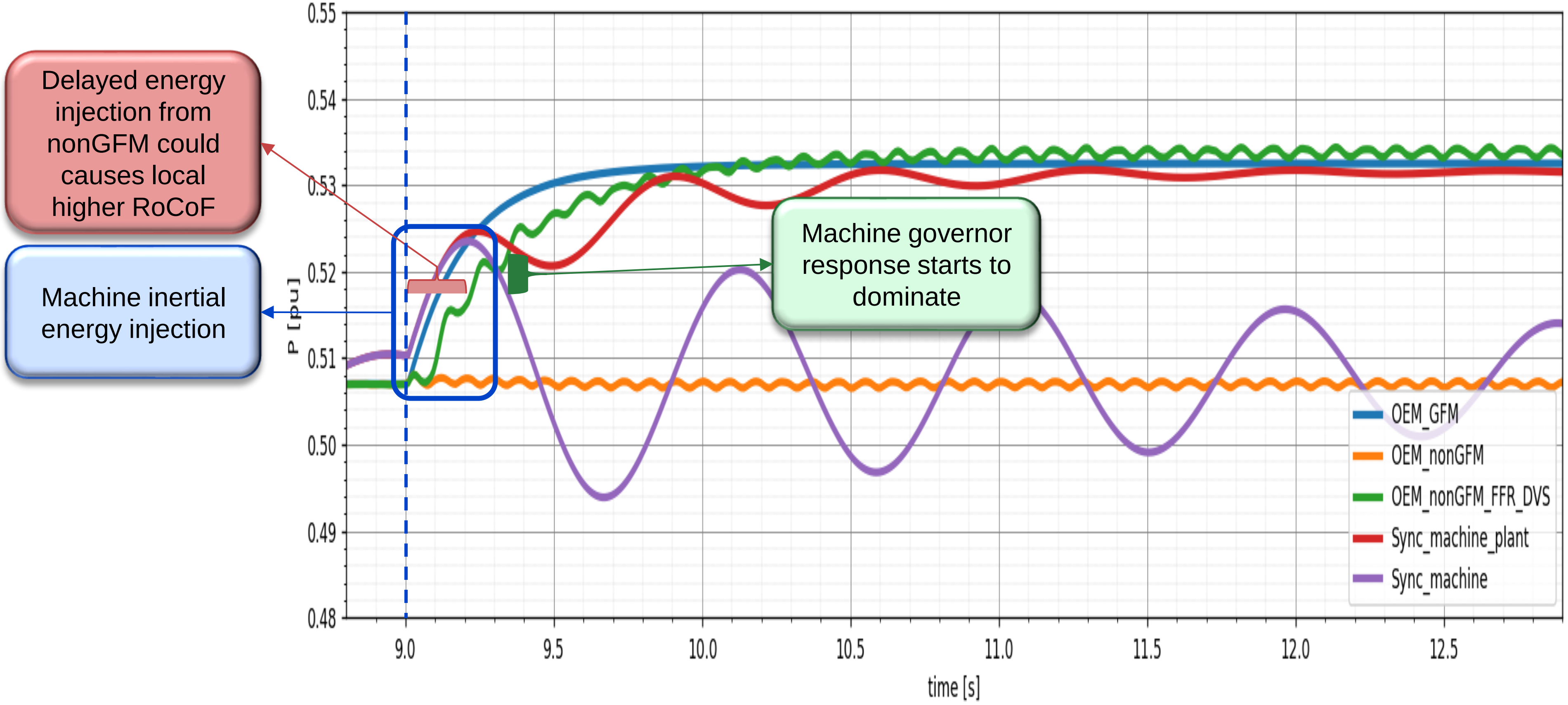
How Do Different IBR Controls (GFM vs. GFL) Impact the IBRs’ Contribution to Frequency Response?

- In an event of frequency disturbance, the GFM control naturally allows its power output to increase instantly and subsequently adjusts its angle according to its internal active power control strategy (droop, VSM, etc.)
- However, **GFL** converters can also be **parameterized** to provide similar fast frequency response. The only minor difference is in the first few cycles.
- This minor difference is expected to **not** bring significant changes to system **frequency nadir**. For the sole purpose of frequency response, GFL with FFR is usually sufficient.
- In cases where **RoCoF** is a concern for loss-of-main protections, the benefit of GFM may be analyzed and quantified, which may further inform procurement and market designs.
- While the difference between GFM and GFL **in frequency support provision** is limited, GFM can bring benefits to other aspects, such as stability.
- **Having enough energy reserve and headroom that supports fast response is essential!**



GFM vs. GFL in Frequency Response Provision

Energy injection timeframes from synchronous machine compared to energy injection timeframes from IBR

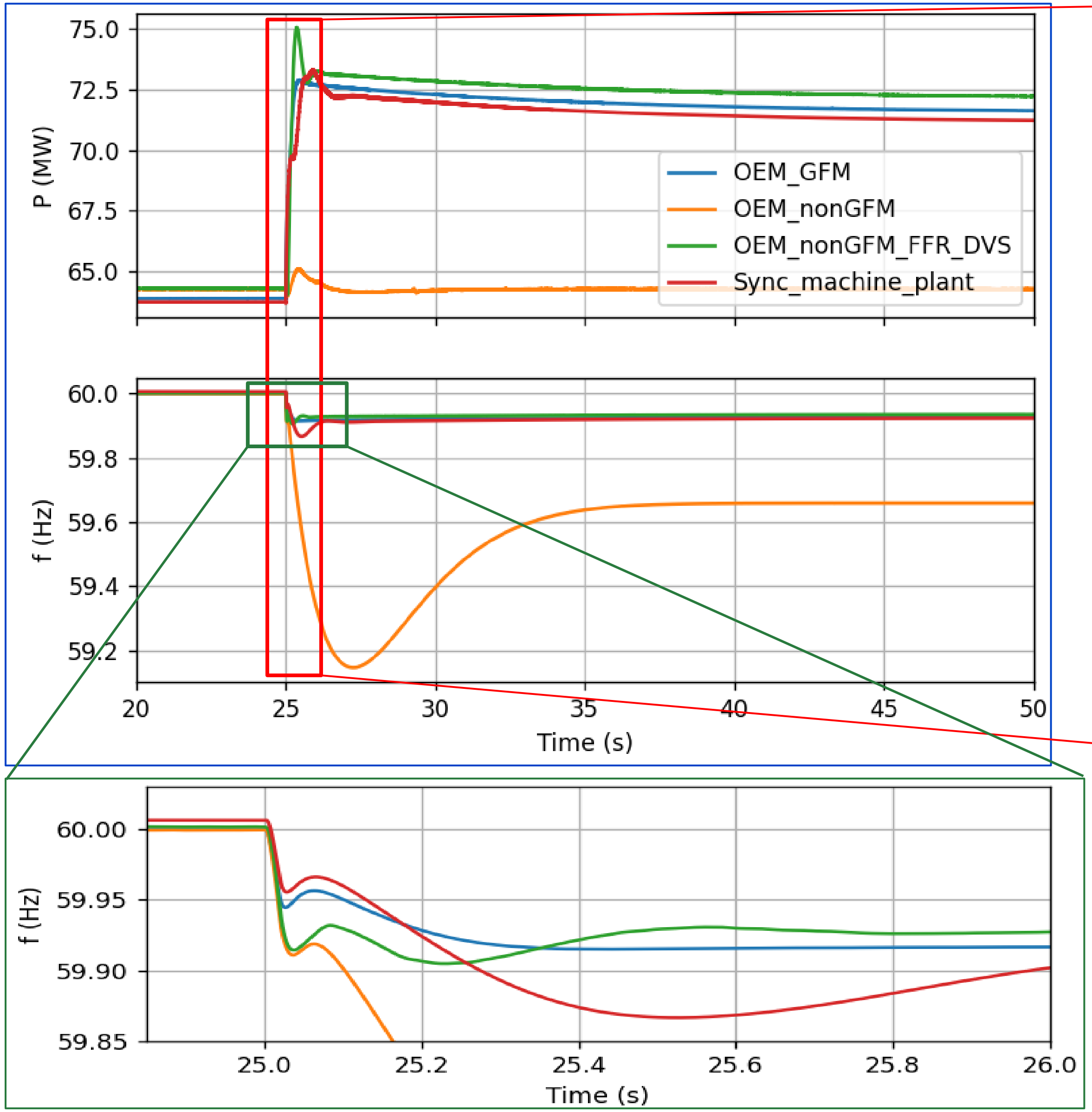


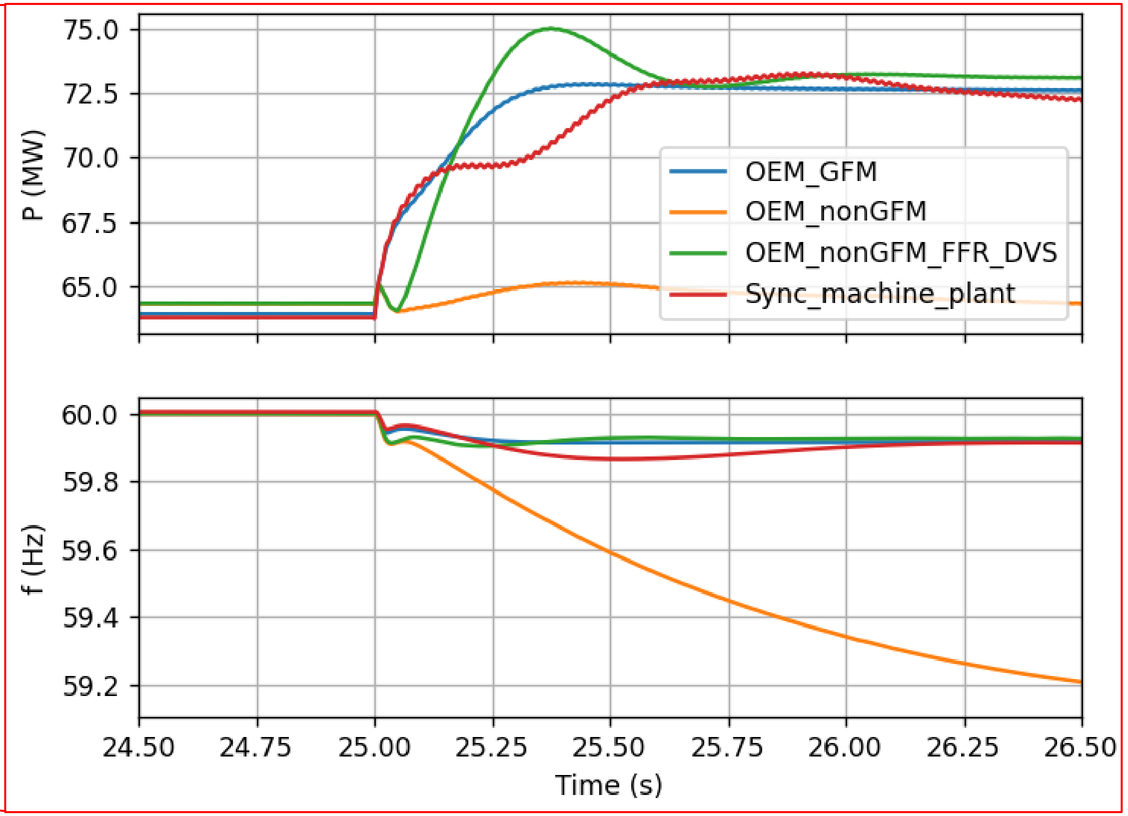
- Step change in network frequency of 0.025Hz at SCR 1.2 and X/R of 10.0
- Synchronous machine assumed to have H = 2.5s
- Synchronous machine plant governor time constant of 0.25s

- nonGFM IBR energy injection delayed by few cycles
- Fast frequency response (FFR) from nonGFM IBR delivers response within 1s

Reference: Frequency Response Primer: A Review of Frequency Response with Increased Deployment of Variable Energy Resources, EPRI Palo Alto 2018 3002014361

Consider a 6% increase in load in a low inertia system





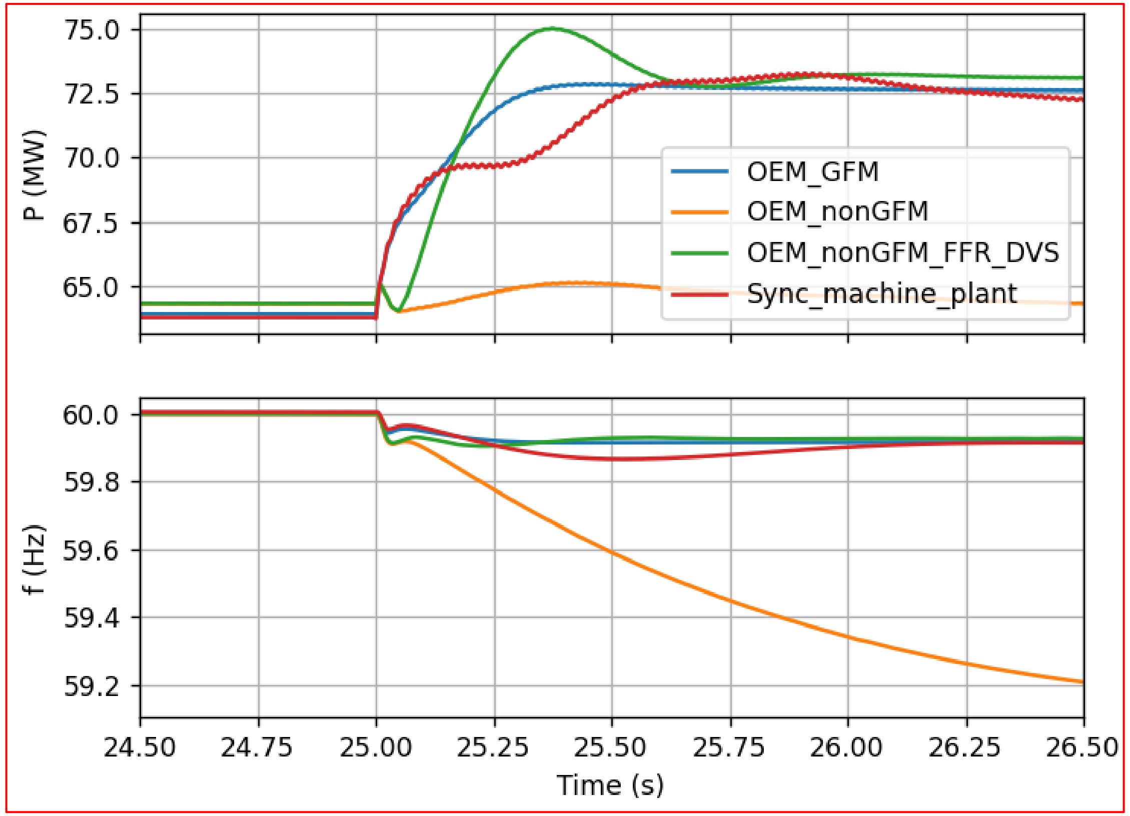
3 cycle ‘delay’ in response from non-GFM IBR with FFR and DVS

Difference in RoCoF over 100ms:
GFM = 0.502 Hz/s
nonGFM with FFR and DVS = 0.707 Hz/s

Consider a 6% increase in load in a low inertia system

- In the first 3 cycles:
  - GFM and Sync machine provide approximately 0.03kWh energy more than GFL resources

- But over 1 second
  - GFM, Sync machine, and GFL+FFR+DVS all provide similar energy of 2.2 kWh



Summary

- **Inertia Regionalization**
  - Reducing inertia and uneven distribution – Regionalization analysis helps identify clusters and assess regional inertia risks.
  - No time-domain simulation needed for the analysis, but the result informs further detailed time-domain studies as necessary
- **Frequency Response Deliverability**
  - Screening method for identifying locations with high risks of electromechanical instability when delivering frequency response.
  - Key factors affecting the stability: regional inertia, area connection strength, IBR frequency response characteristics.
- **High Penetration Bulk Power System Frequency Assessment**
  - IBR impact on inertia and frequency performance
  - IBR frequency support service provision and performance
  - Regional inertia and frequency dynamics assessment
  - Resource comparison in providing frequency support

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