Grid Stability Services:

A Framework for Quantifying Supply and Demand of Grid Stability Services

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Contents

About this deck:
This slide deck is an annotated presentation capturing the grid stability services framework developed by this team, and its demonstration on the SPP system model.

Please refer to the "Notes" feature of the PowerPoint presentation for additional details on the slides.

Motivation & Industry Context

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Key Questions for Grid Stability Services

Stable Operation at 100% IBR is Possible… What Stability Services are Needed to Get There?

What services do we need?

It's more than just inertia…

How much?

What are the units? How do different grid conditions change it?

How fast?

Fast and slow and sustained, it's all needed.

Where?

Location matters… more for some services than others.

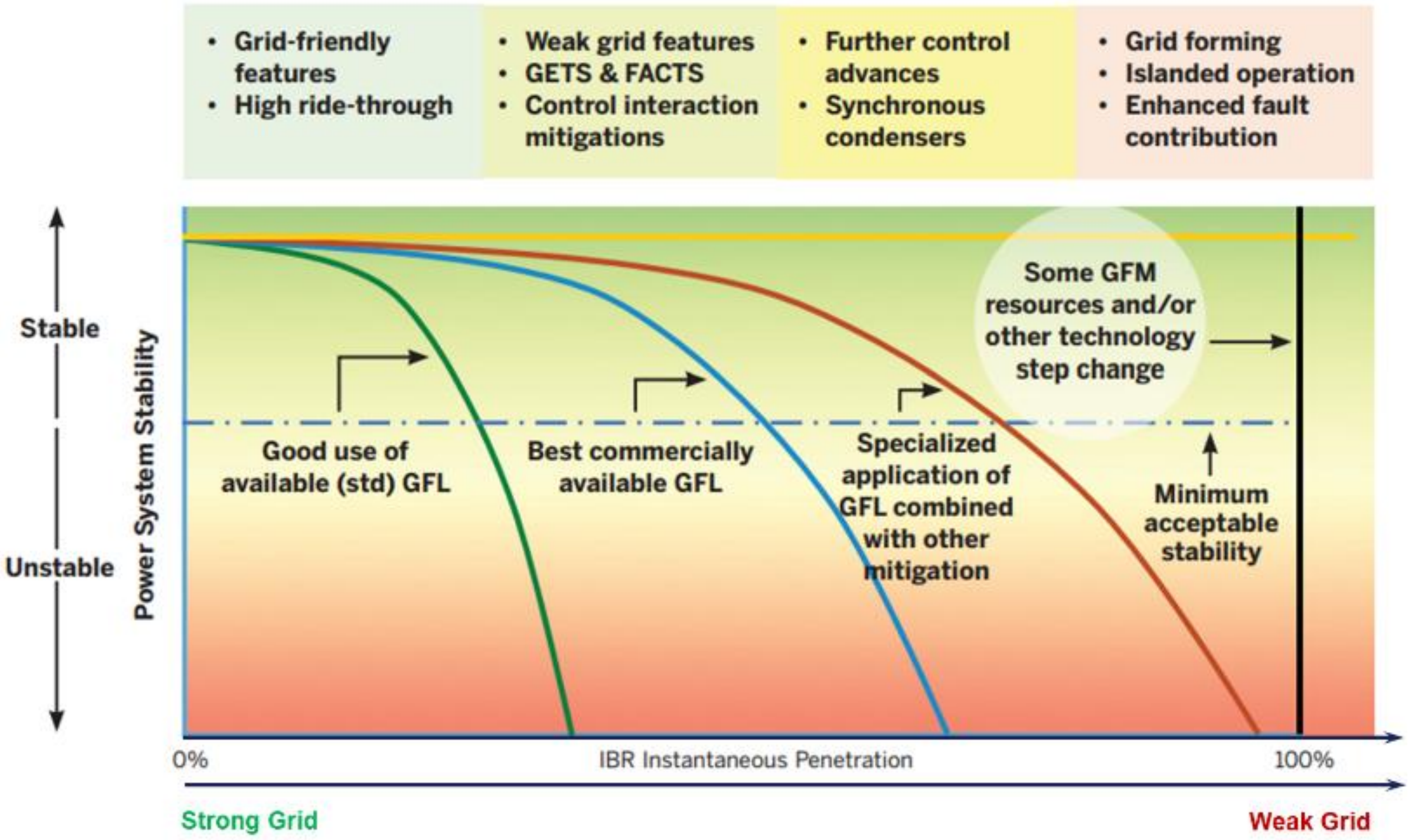
There has been substantial progress in the industry here

Our work is focused on **quantifying** services

- Generalized
- Technology agnostic
- Repeatable

To develop a **framework** that can be **rolled out to all system operators & planners**

Growing Shares of IBRs and Changing System Needs



[An Overview of Grid-Forming Inverter Technologies and the Readiness of Power Systems Worldwide to Deploy the Technology]

Efforts Around the World

- System needs are evolving due to proliferation of IBRs and decommitment of synchronous generation.
- A variety of efforts on grid services is happening around the world, e.g. NESO, AEMO, EirGrid and ERCOT have relatively new services, with varying temporal and locational targets
- This project aims to provide a framework to help define those targets and evaluate capability of various resources to provide the services.

		NESO	AEMO	EirGrid	ERCOT
Inertia	Timeframe	–	–	–	–
	Locational?	System-wide	System-wide	System-wide	System-wide
Short Circuit Level	Timeframe	–	–	–	–
	Locational?	Regional	Regional	Regional	Regional
Active Power	Timeframe	Initial response <0.5 s, full response <1 s	~1s, dependent on voltage recovery	< 2 s	~0.25s or ~0.5s*
	Locational?	System-wide	System-wide	System-wide	System-wide
Reactive Power	Timeframe	Initial response < 0.02s, Full response < 0.12 s	Initial response <0.04s, Full response <0.08s	Rise time 0.04s, Settling time < 0.3s	<0.5 s
	Locational?	Nodal	Nodal (case-by-case)	Nodal	Nodal

* Different requirements apply to different types of service

Grid Stability Services Framework

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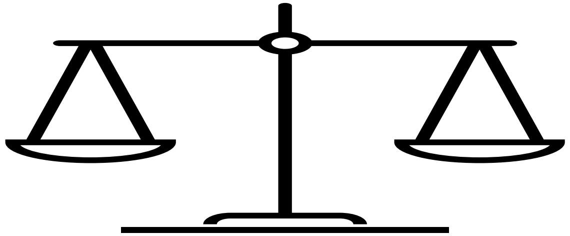
Stability Services Framework Overview

Provision of Services
(Resources + Transmission)



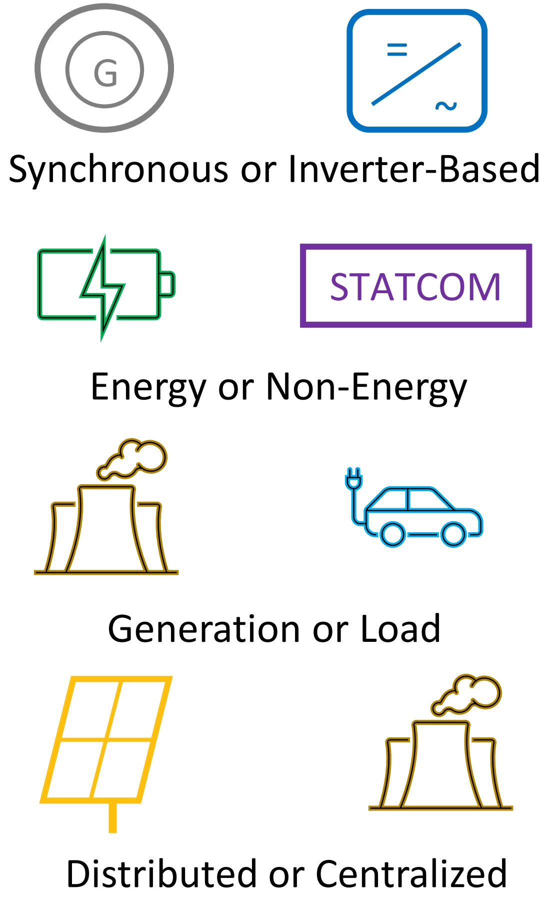
Need for Services
+
Acceptance Criteria

Power Type	Timeframe	Location	Operations
Active	Fastest (cycles)	Local/Regional	Headroom
Reactive	Medium/Slow (seconds)	Network-Wide	Dispatch, Line loading

What Can Provide These Stability Services?

Resources, Direct Impact to Services

- All resources may provide one or more of the services
- The services rendered depend on the resource's characteristics & operating condition



Transmission, Indirect Impact to Services

Can "move/deliver" services to different locations

What's Not in Scope

System Restoration

- Sometimes shown as a "black-start" service
- System restoration is far more complex than just having black-start resources

Protection

- Sometimes reflected as a service for "short-circuit current/level"
- Highly dependent on the protection scheme, communications, etc.
- Some protection schemes may pose a demand for certain other services like fault current, zero or negative-sequence current, but we're not tackling this here

Definition of Services

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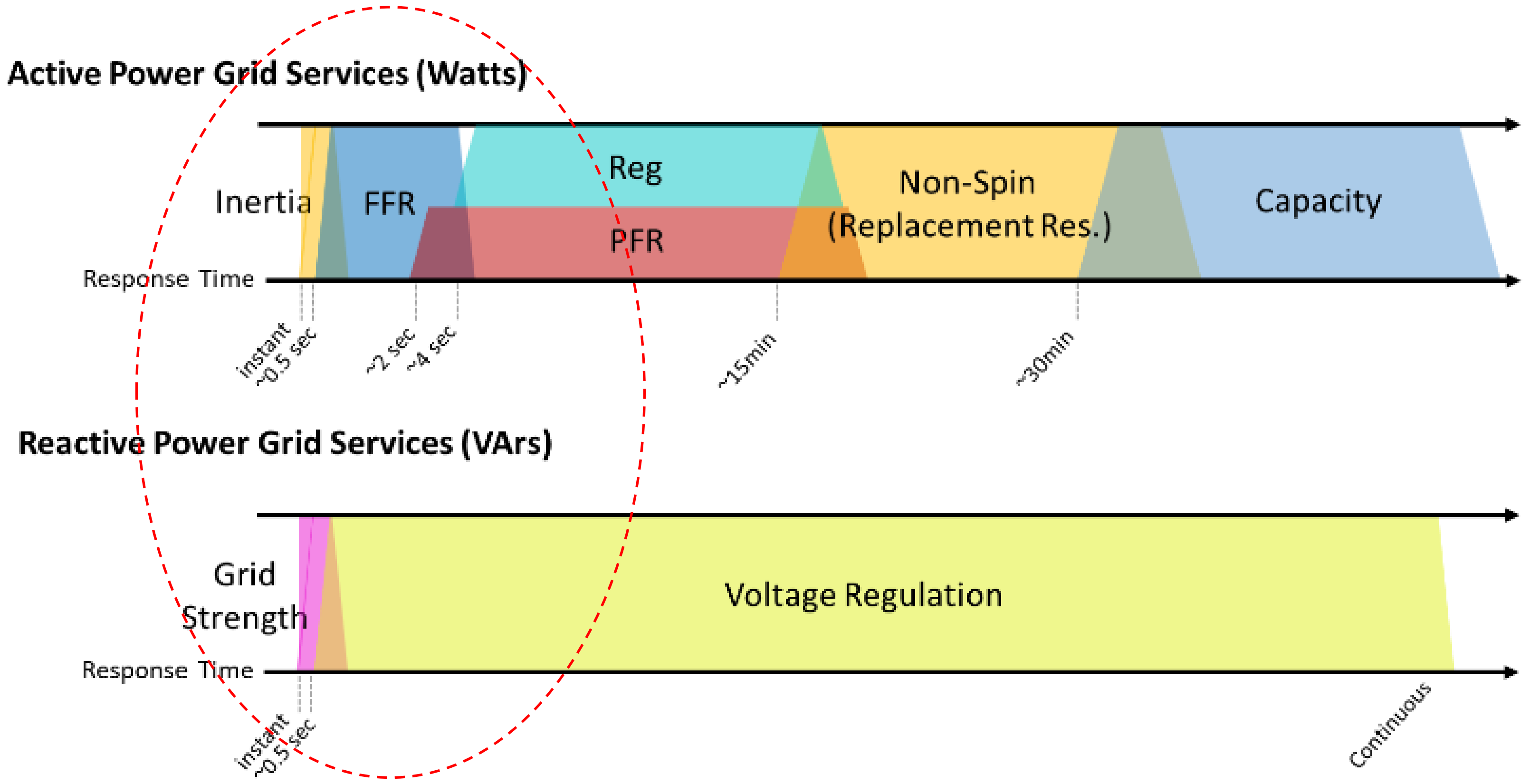
Power Type and Timeframe



Our stability work will focus on the services in the shorter time frames

Timeframe: Assessing Performance of Resources

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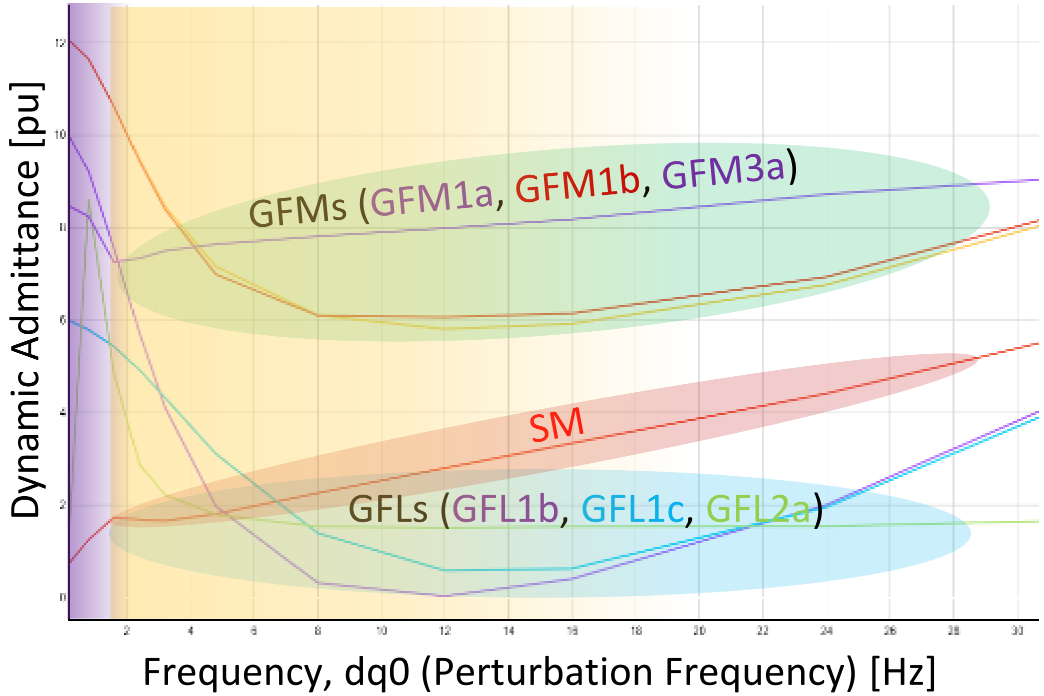
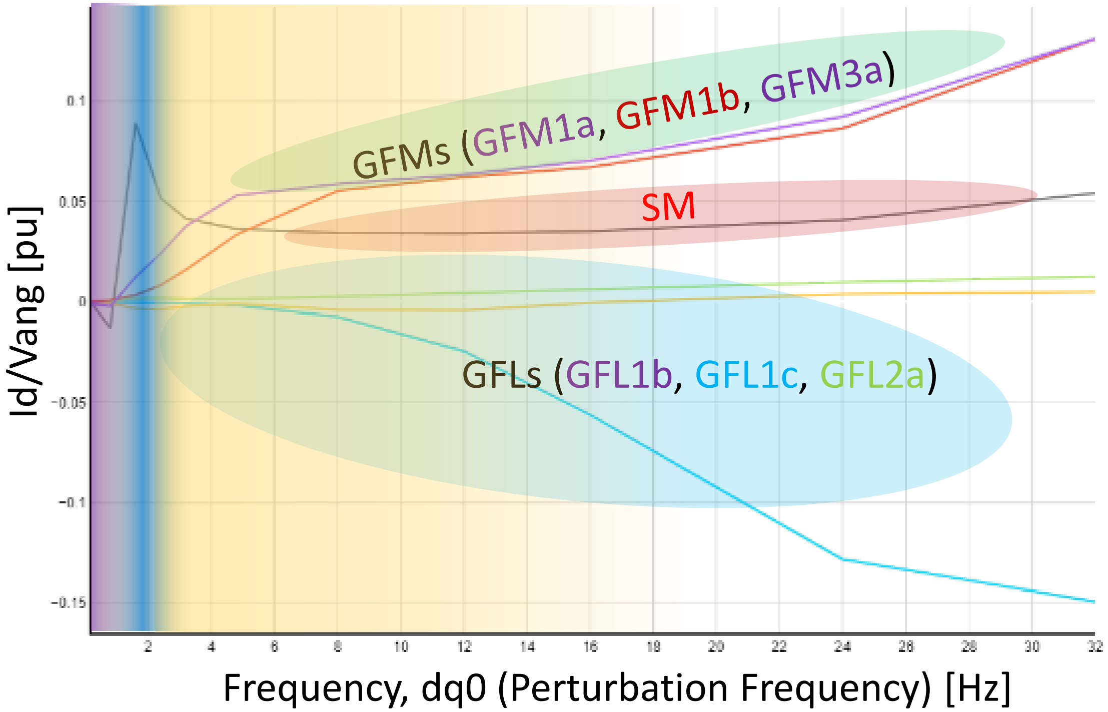
Slower (Plant Voltage Regulation) Services | Fast (“FFR”) Services | Fastest Services “Inertia” or “Grid Strength”

Reactive Power Services



Active Power Services



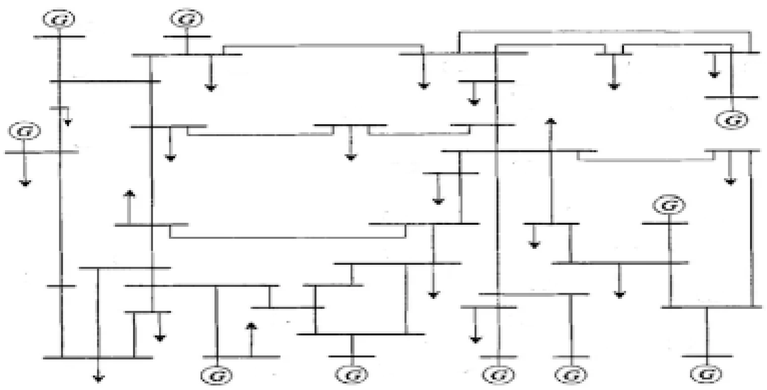
Apply Frequency-Scan Methods to Consistently Assess Responses and Timeframes in a Technology Agnostic Manner

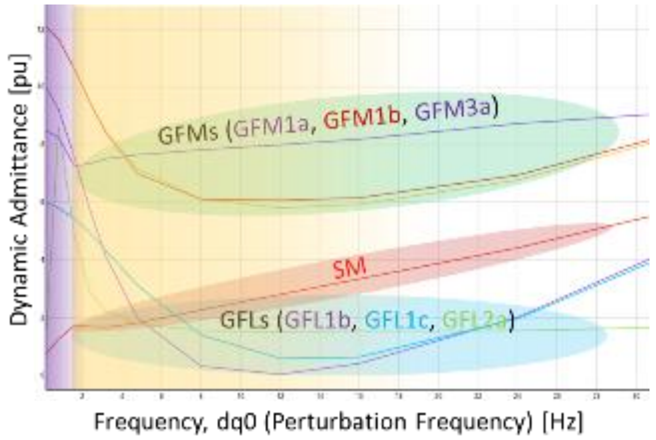
Location: Defining Grouped Regions

- Areas and zones from today's powerflow models are based on ownership/control regions
- It does not reflect the underlying fundamentals of the grid, nor how it is expected to evolve

There are two major physical attributes that guide our regional grouping:

Network connectivity (admittance matrix) AND Resources online & their characteristics





Location: Buoy v. Breakwall Resources

"Buoy" Resources

- Resources with little provision of stability services, particularly in the fastest timeframes
- i.e., GFL resources, small resources, resources with little/no headroom

https://www.pexels.com/photo/green-bouy-on-ocean-2350584/

"Breakwall" Resources

- Resources with large provisions of stability services, particularly in the fastest timeframes
- i.e., Large SM & GFM resources with headroom

https://www.pexels.com/photo/stone-wave-breaker-on-sea-shore-5113384/

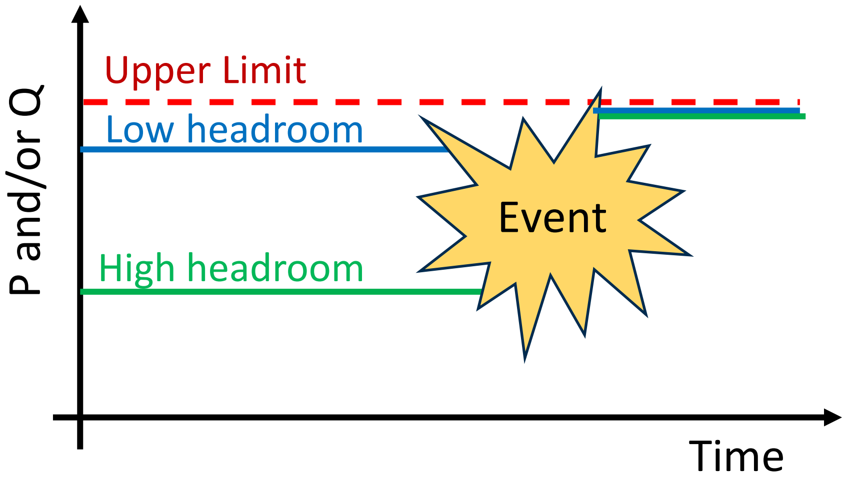
Operations: Grid Condition-Dependency

Provision-Side: Headroom constraints

- Margin to Active Power Limits – some resources may allow temporary limit exceedance
- Margin to Reactive Power Limits – some resources may allow temporary limit exceedance or trade-off active power

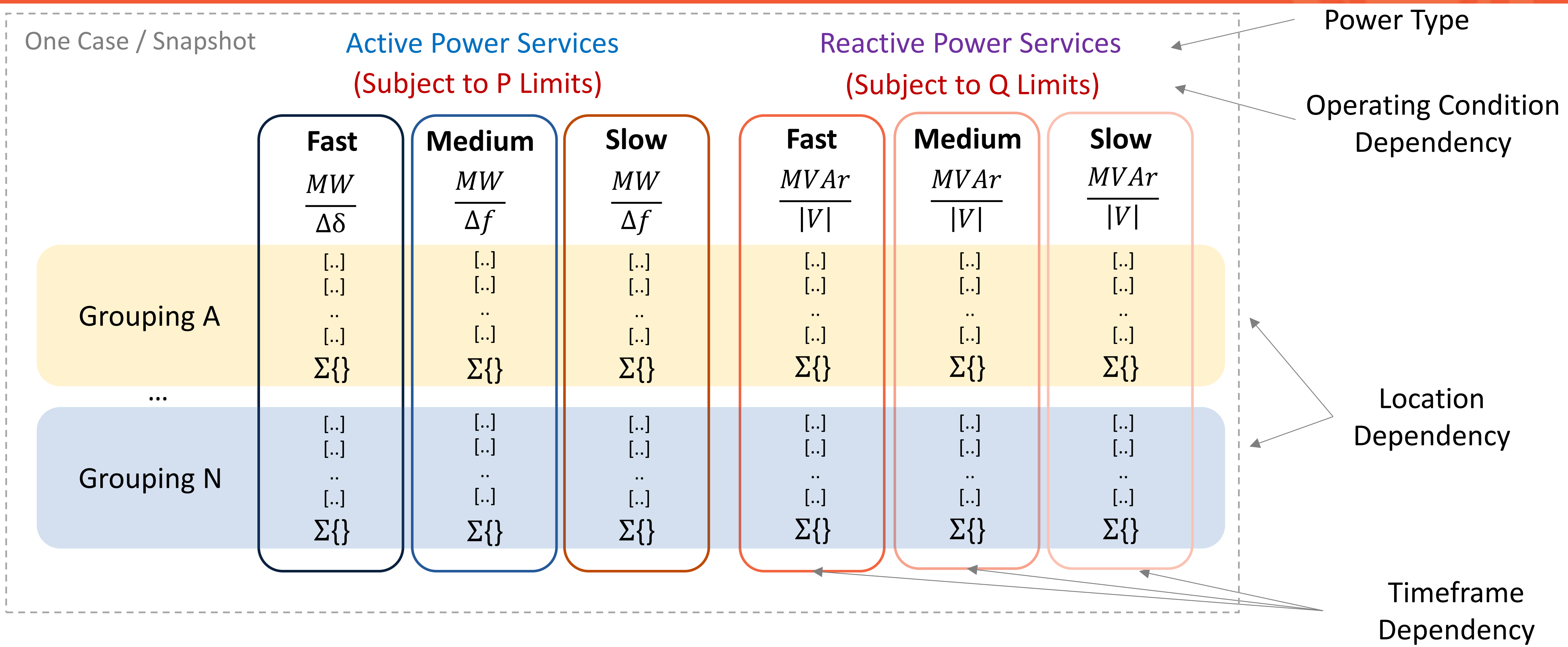
Need-Side: Contingency Size

- Generation Dispatch – Higher dispatch results in a larger P-loss event
- Transmission Line Loading – High loading results in higher Q (I^2X) losses post-event

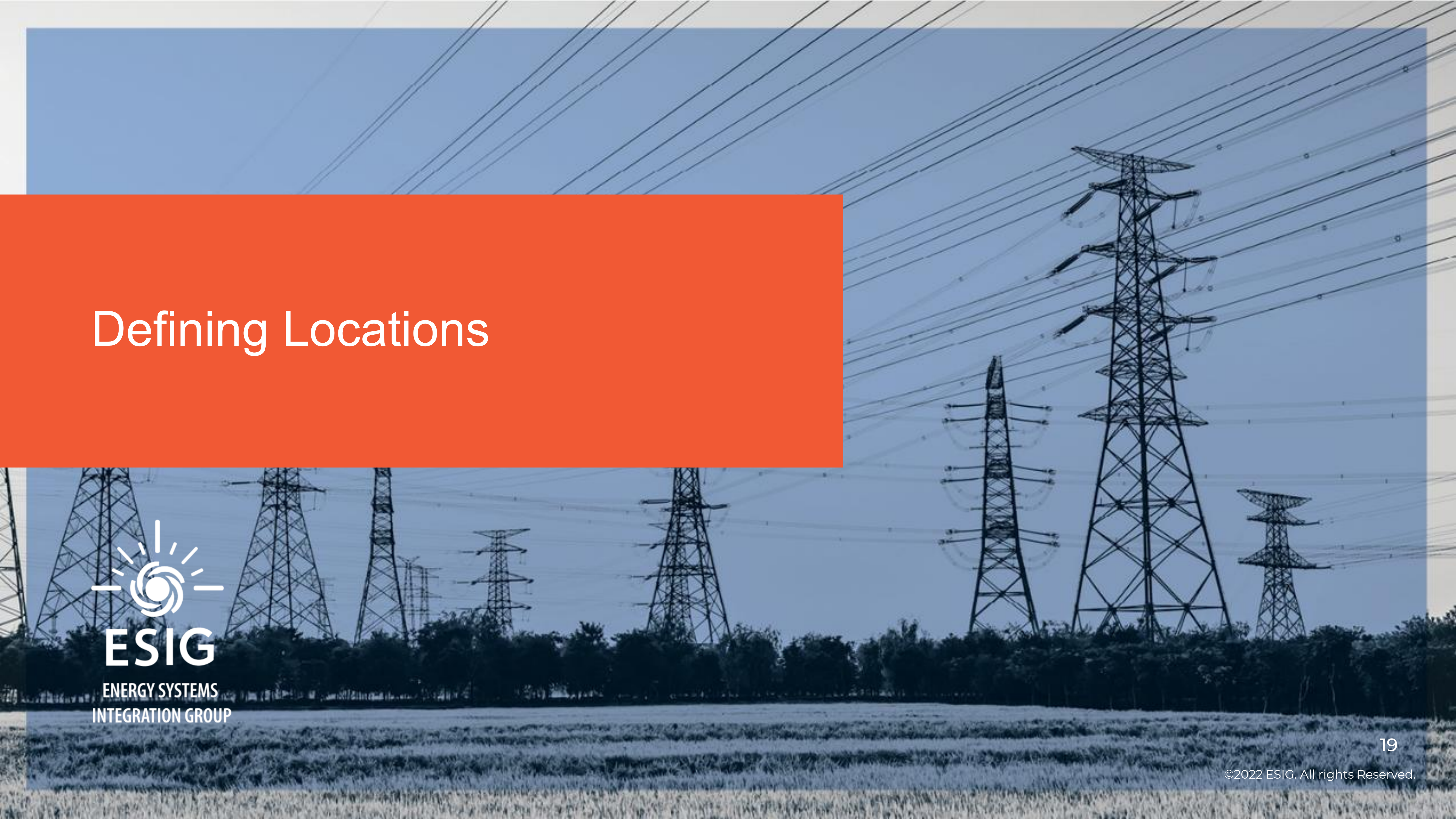


Bringing it Together, Provision Side

4 Pillars of Framework Covered



Defining Locations



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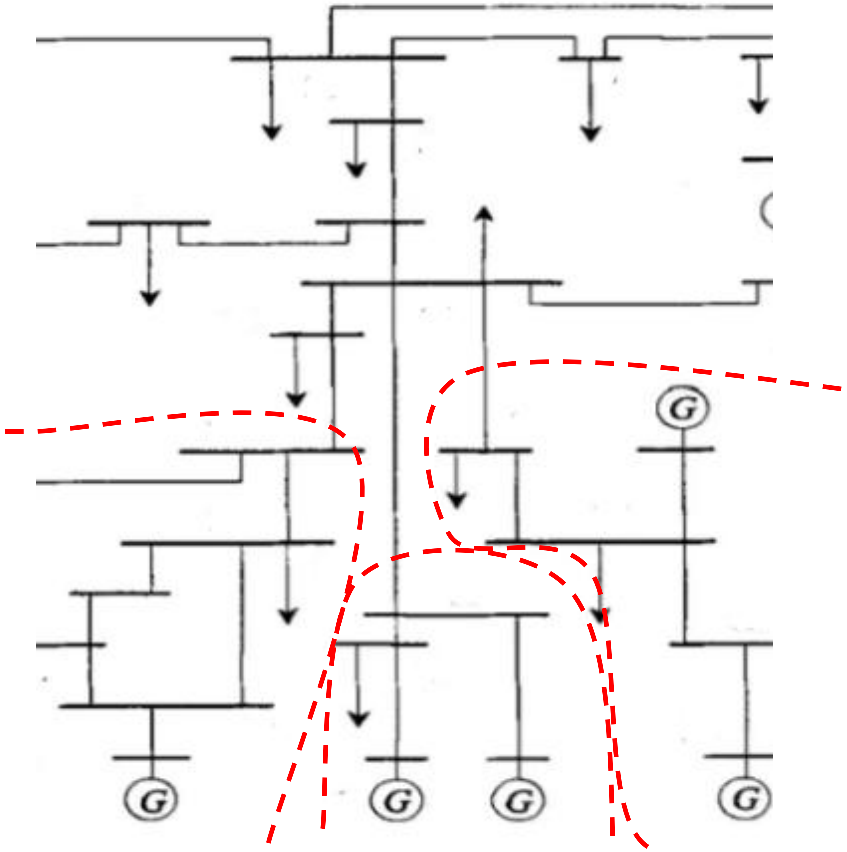
Regionality of Services

Reliability within a region is affected by many factors (power transfer, available reactive power support, relevant contingencies…)

- System boundaries are traditionally determined based on…
  - Ownership
  - Operational boundaries
  - Historically observed behavior
- In SM-dominant power systems, this is sufficient…
  - IBR dynamic performance can vary more than SMs depending on the plant software
  - IBR dispatch can shift quickly due to changing weather conditions, stressing system stability

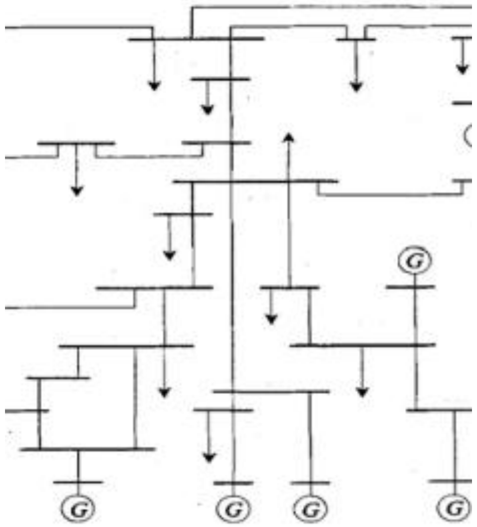
There is a need for a reliable and technology-agnostic method to determine the appropriate study boundaries based on transmission *and* generation dispatch

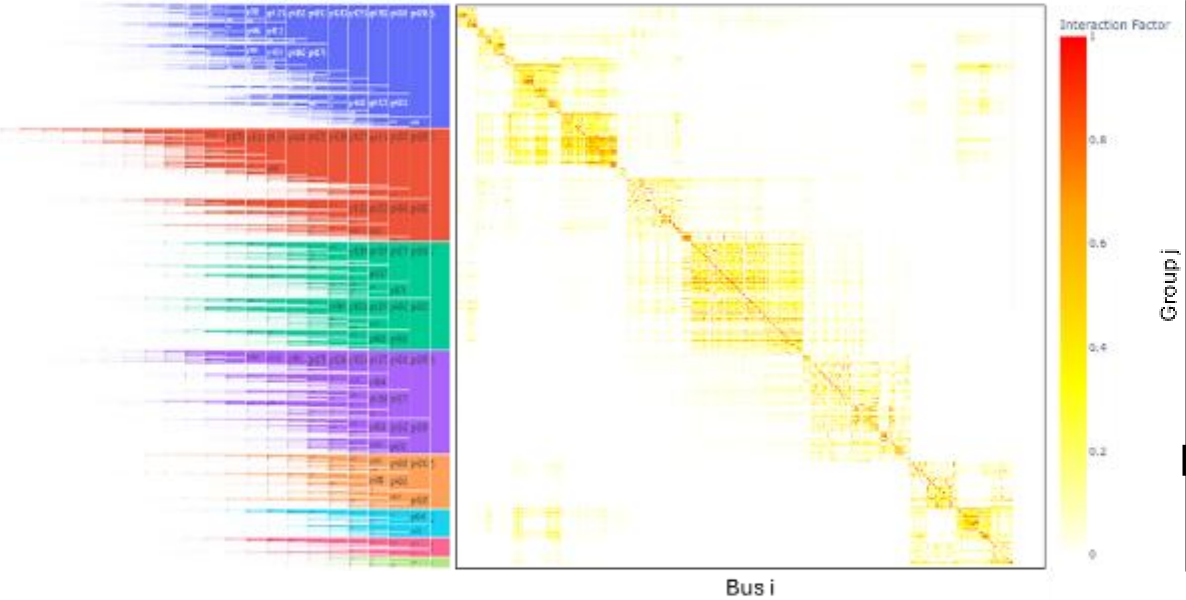


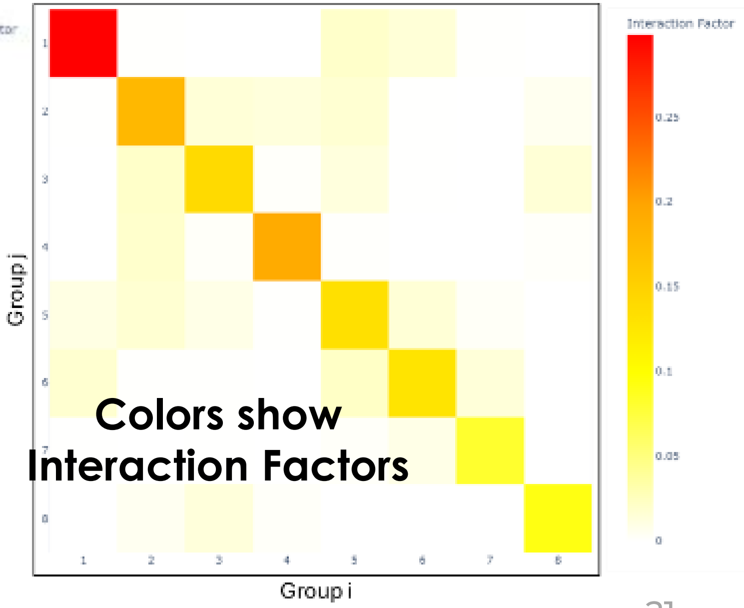
Proposed Network Grouping Process

Objective: Group not by historical/ownership boundary, but by electrical attributes
Electrical attributes include both **transmission topology** AND **resource mix characteristics**

System Data → Hierarchical Grouping Algorithm → Regional Groupings



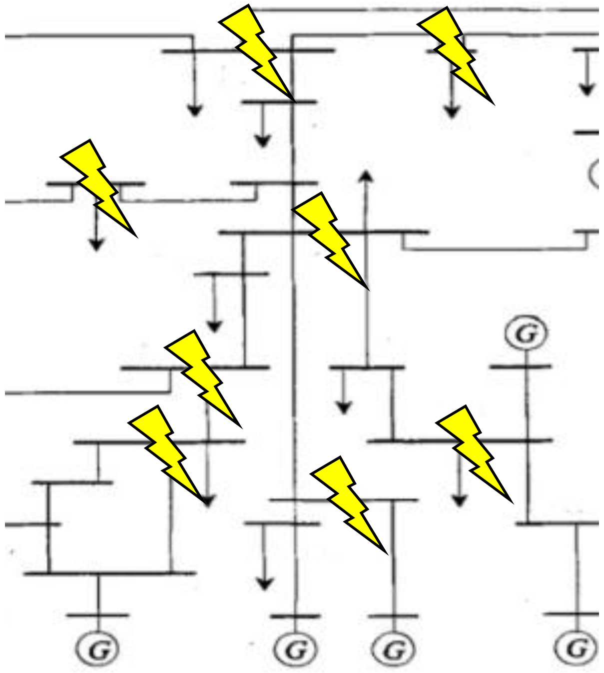




Interaction Factor Calculation

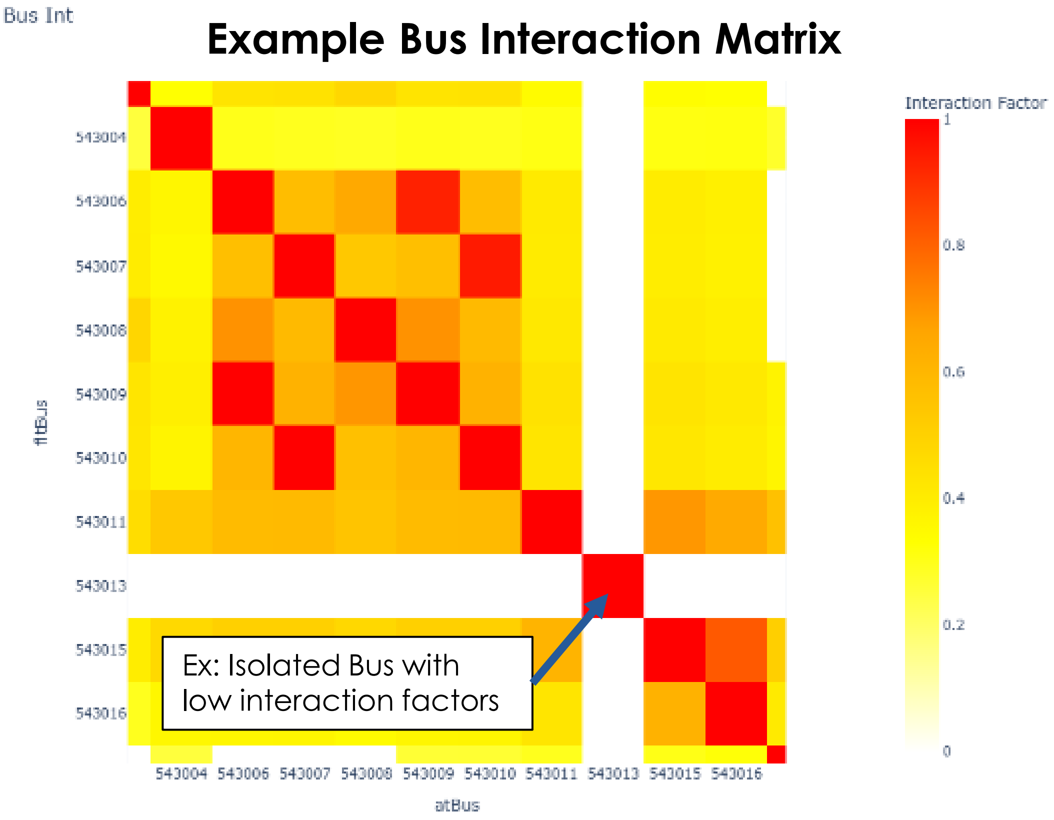
Short-circuit fault analysis is applied to determine the interaction factor ('electrical closeness') of transmission buses within the system i.e. which buses will swing together

Example System Powerflow



IEC 60909 SC Fault Analysis at Every Bus in Network

Example Bus Interaction Matrix



Where interaction factor (IF) is:

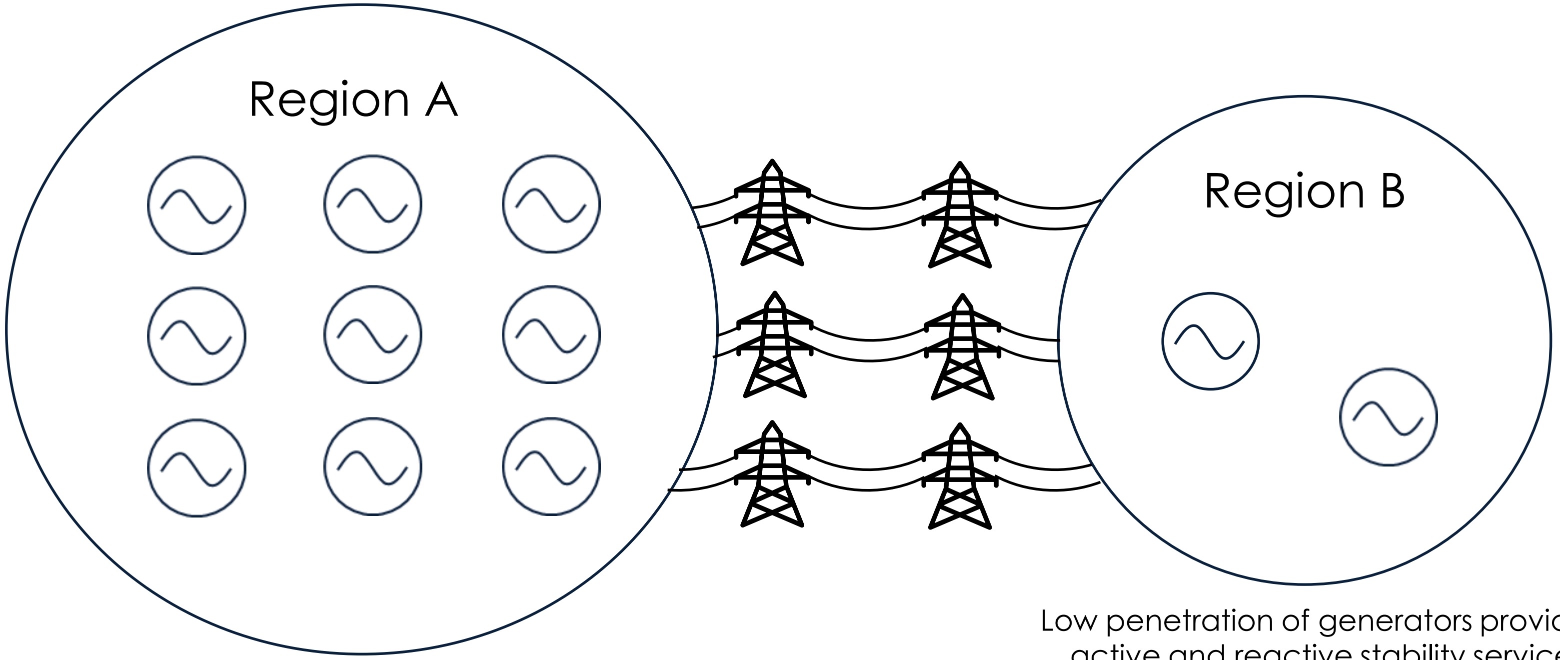
$$IF_{ij} = \frac{\Delta V_i}{\Delta V_j}$$

Regional Grouping In-Practice

Consider:

- Fault in Region A causes a large voltage decrease in Region B because B does not have much local reactive power services to prop up voltage in B. This results in a high interaction factor for A → B.
- Fault in Region B does **not** cause a large voltage decrease in A because the stability support services in A support voltage in A. This results in a low interaction factor for B→ A.

This asymmetry highlights a stability boundary in the system!



High penetration of generators providing active and reactive stability services

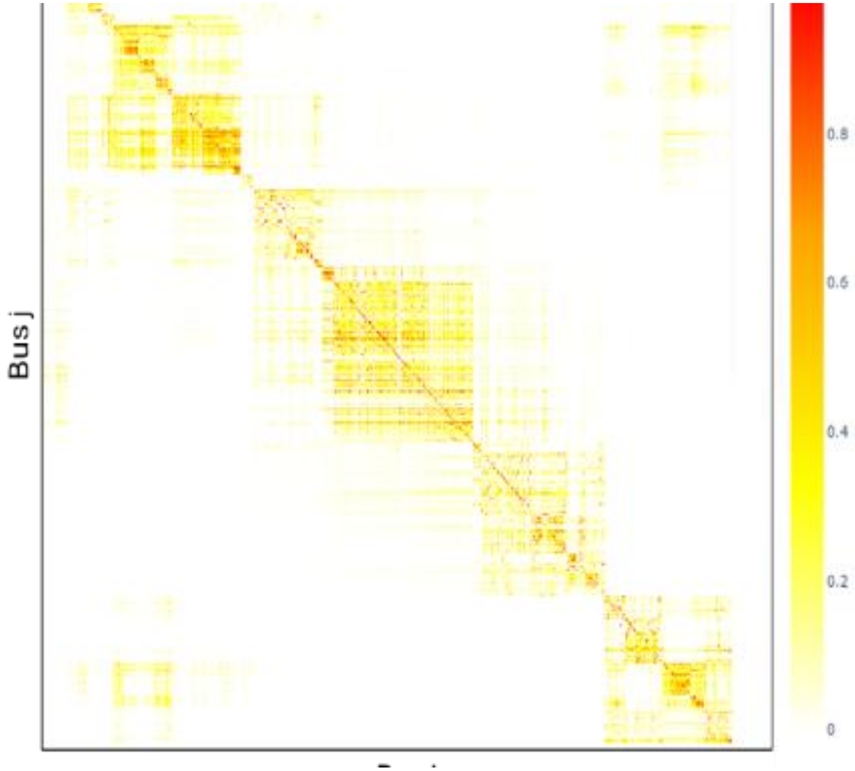
Low penetration of generators providing active and reactive stability services

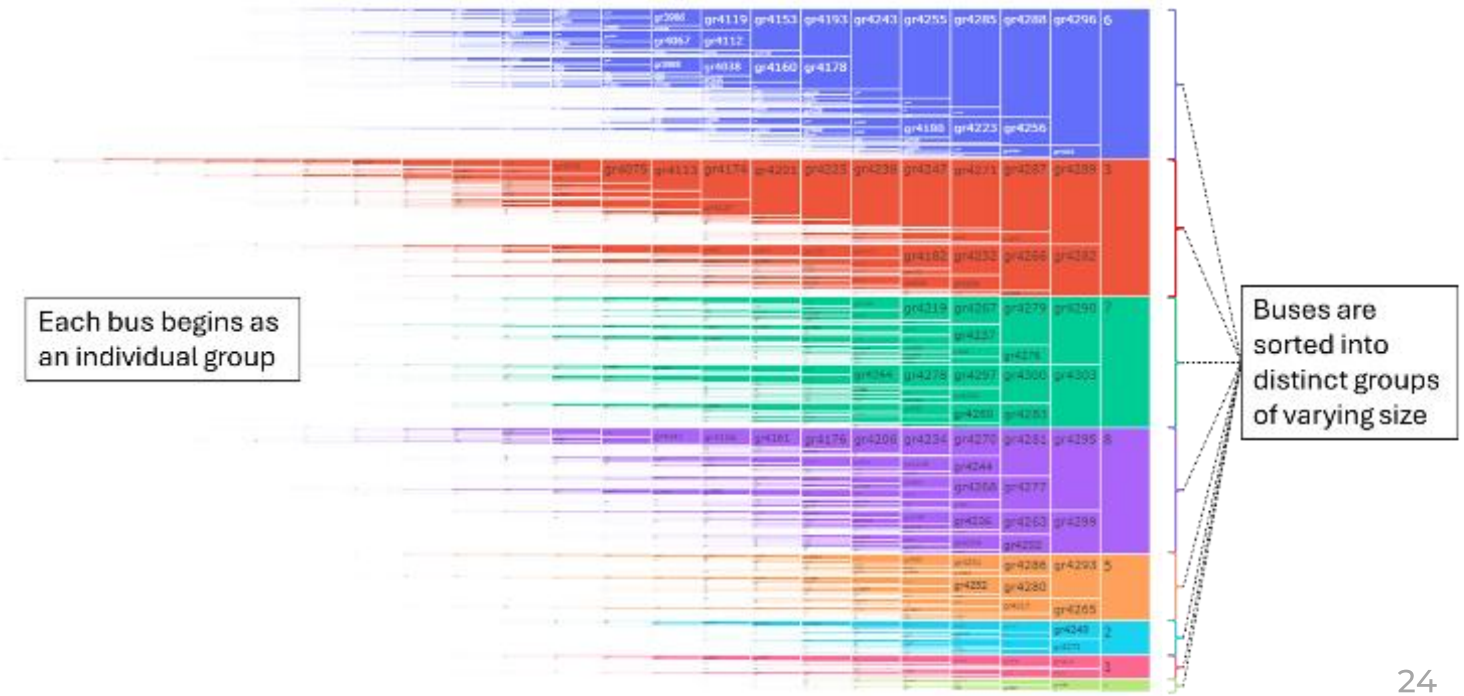
The grouping algorithm captures this boundary by accounting for generation mix as well as transmission network topology

Hierarchical Grouping Methodology

Buses are grouped in hierarchical order based on the highest interaction factor.

Hierarchical Grouping Algorithm

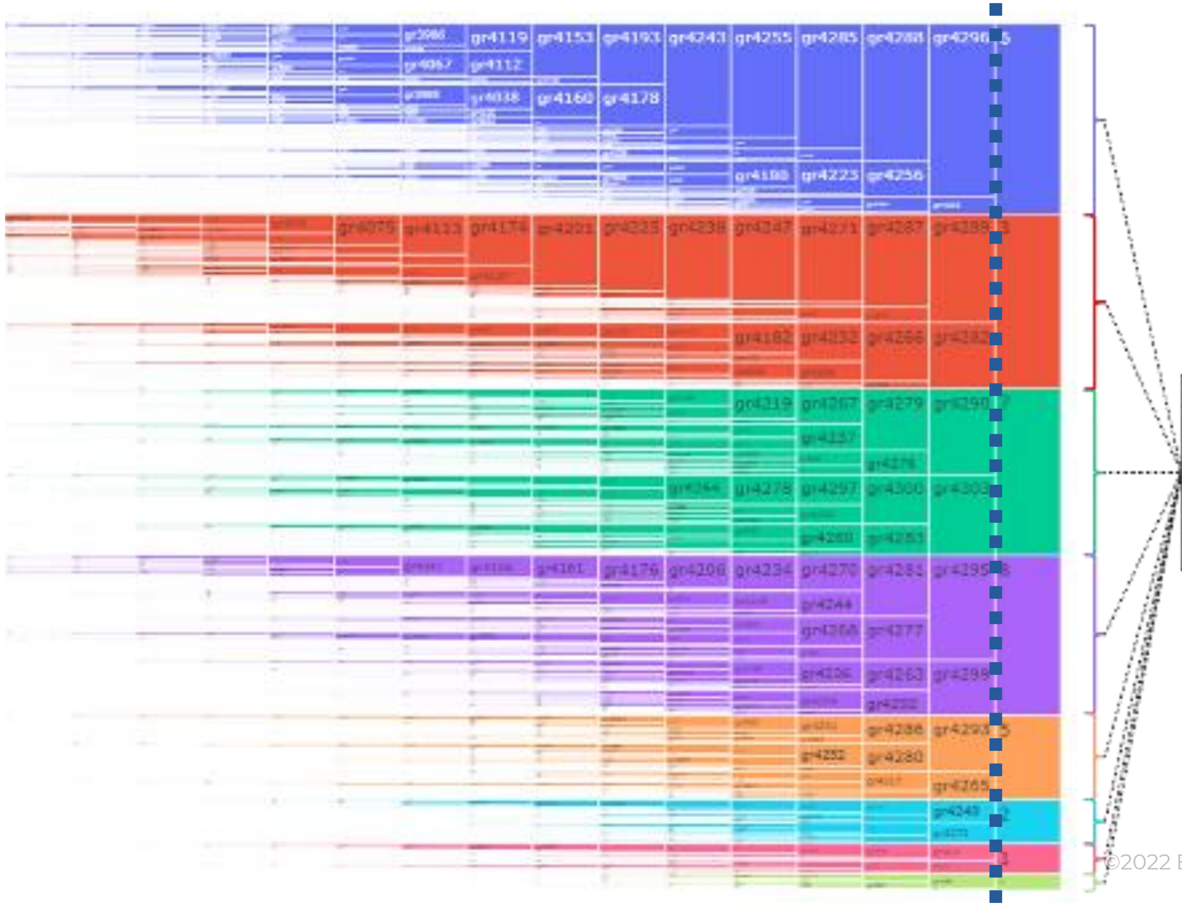




Choosing an Interaction Factor Threshold

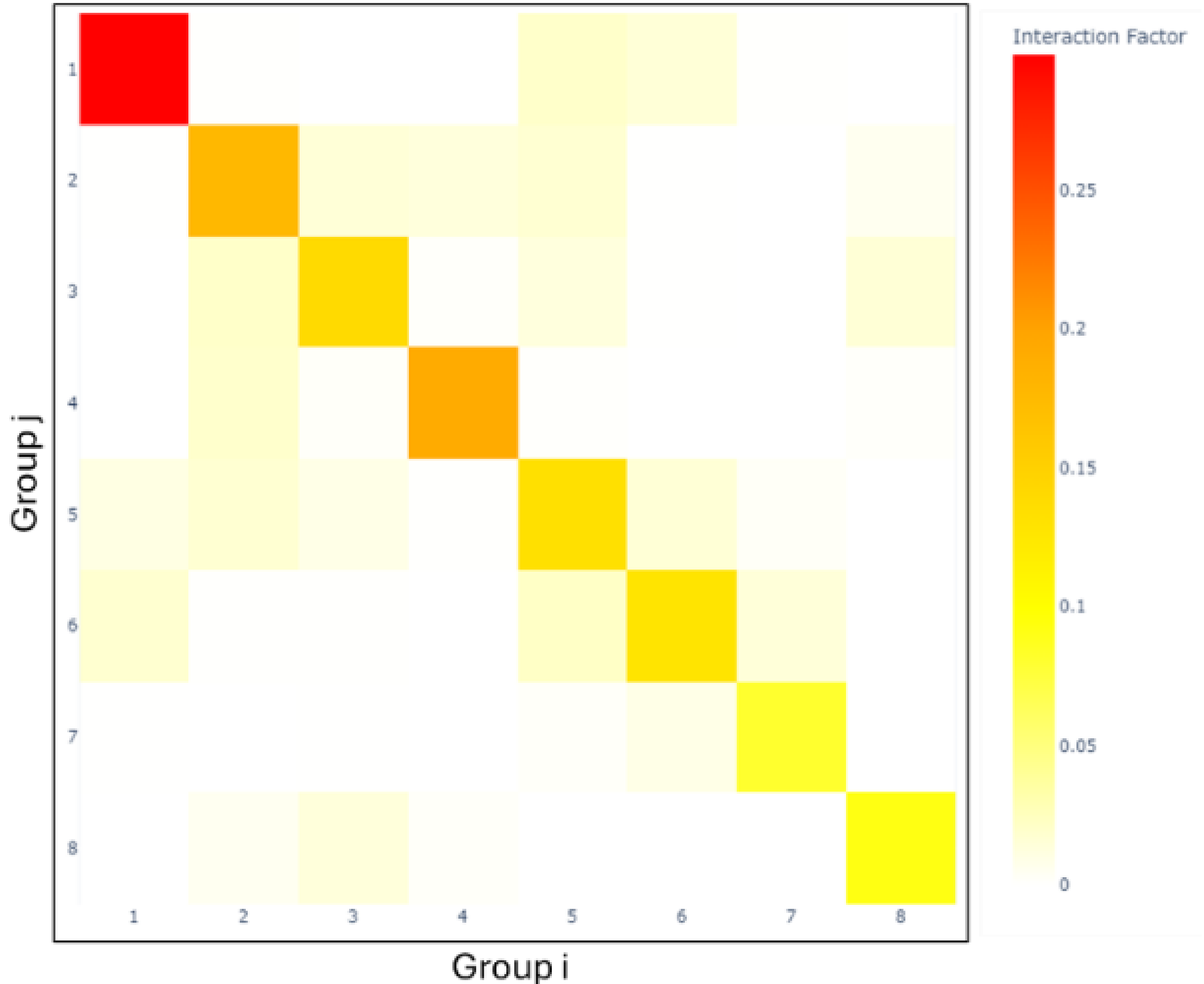
Selecting the Number and Size of Groups (Granularity)

- Each bus begins as an individual group
- The hierarchical grouping algorithm proceeds with grouping until there are no two groups with an interaction factor above the user-specified threshold
- The granularity of the analysis can be adjusted by tuning the IF threshold (blue dotted line)
- In the example shown here: 8 groups are determined using an interaction factor threshold of 0.02

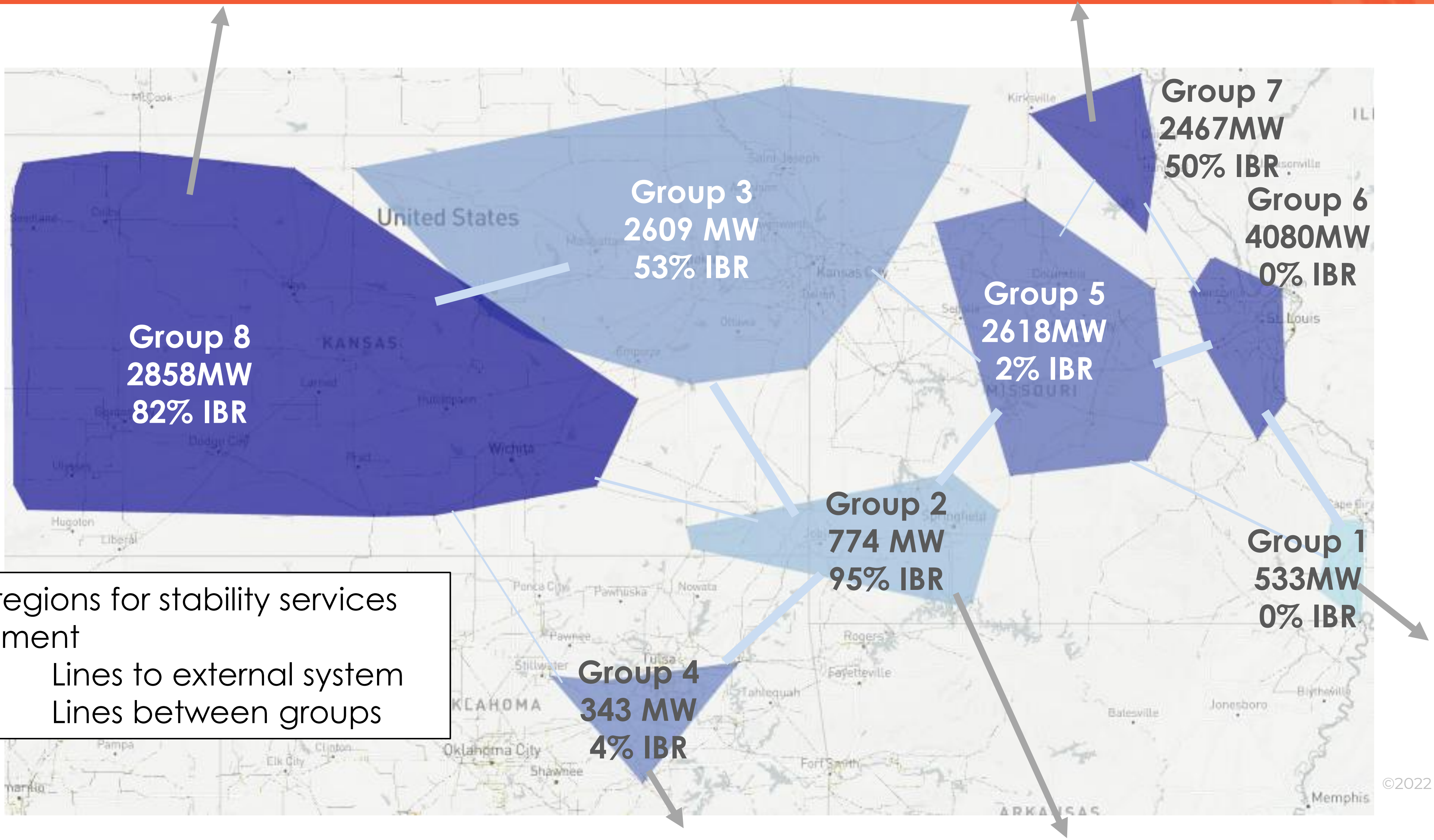


Groupings - Interaction Factor Matrix

For our demonstration on the SPP system, a 2157 bus test system is aggregated into eight groups…



Groupings - Geographic Mapping



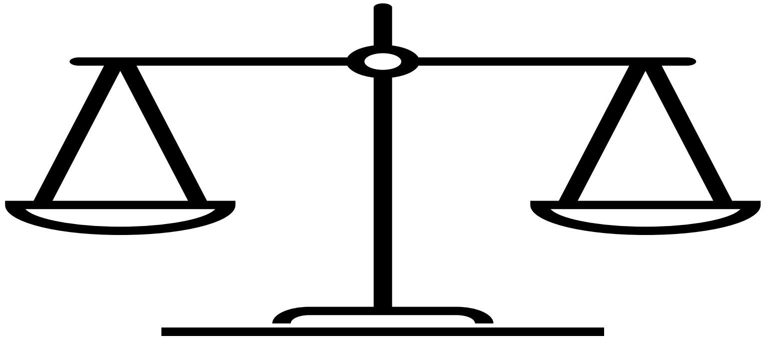
Eight regions for stability services assessment

- Lines to external system
- Lines between groups

Stability Services at Group Level

The stability needs of the system and available stability services are assessed by group

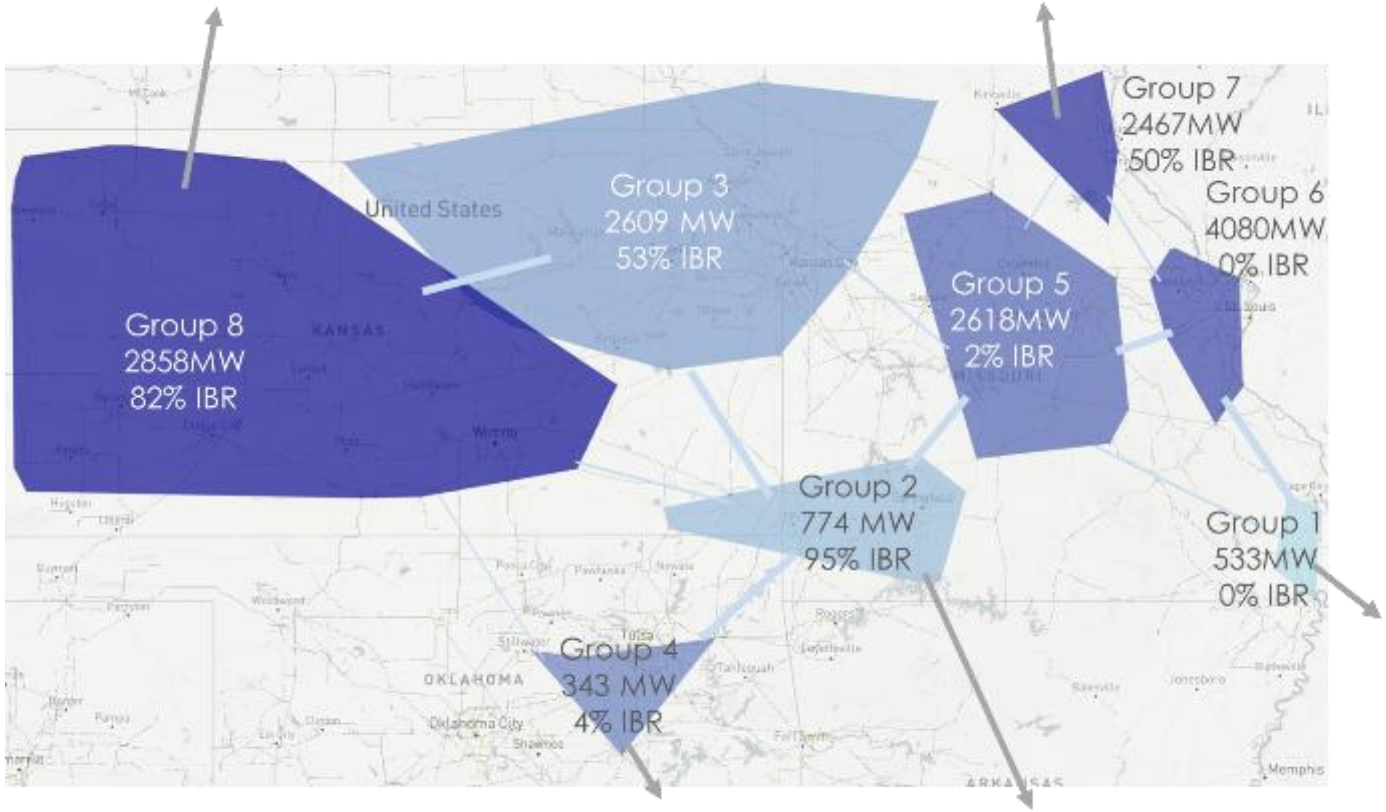
- Calculating stability needs for each group:
  - Generator outages within the group active power service
  - High-impact transmission line contingencies require reactive power services
- Stability services provided by each generator are determined from individual resource characterization and summed by group



Grouping Framework Benefits

Benefits of a Grouping Algorithm

- Based on physics, not historical ownership/control (transmission network data + online resources)
- Repeatable method for identifying system boundaries & interfaces
- Runs quickly, enabling users to see how interfaces move for different scenarios or contingencies
- Can be adapted for different operating conditions or planning scenarios



Provision of Services

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Provision of Services in a Region

- Provision of a service in a region = Σ (provision of services at each resource providing that service)
- Looking at individual unit responses to have a "quick and dirty" idea of how much services may be available, and what devices may be contributing
- Magnitude of response, location (region), and the time frame (s) during which the response is provided – all important factors
- Provision of a service from a device may depend on availability of energy (headroom), and appropriate control functionality and settings

Resources

Resource Name	Rated Output
Resource A Resource B, etc.	[MW], [MVAr]

Sufficiency

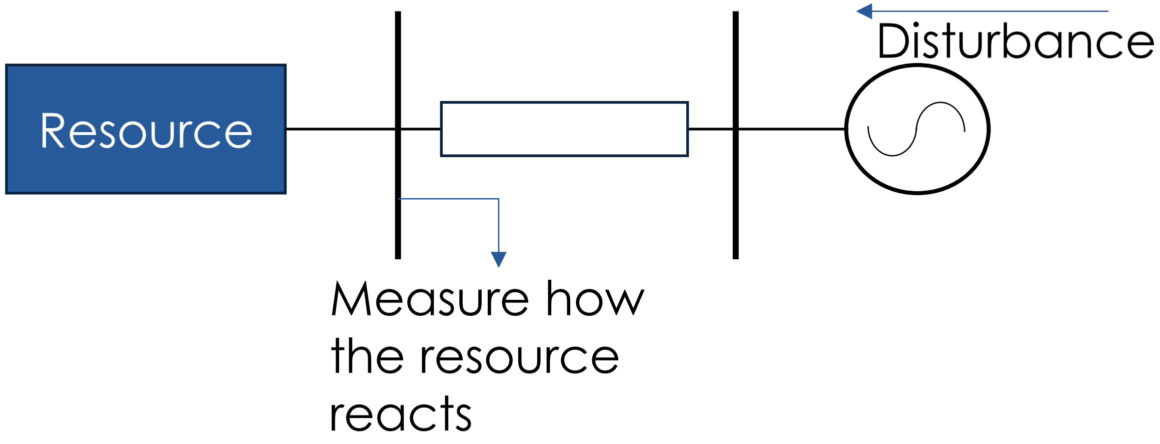
Response Enabled	Headroom
True/False	Per-unit MW on MW base

Timeliness of Delivery

Fast (i.e., Inertial, Grid Strength)	Middle (i.e., FFR, Terminal Vreg)	Slow (i.e., Plant-Level, Governor, Exciter)
< 0.1 seconds $[\Delta P_{pu}/\Delta f_{pu}]$, $[\Delta Q_{pu}/\Delta V_{pu}]$	0.1s – 2.0s $[\Delta P_{pu}/\Delta f_{pu}]$, $[\Delta Q_{pu}/\Delta V_{pu}]$	2.0s – 10s $[\Delta P_{pu}/\Delta f_{pu}]$, $[\Delta Q_{pu}/\Delta V_{pu}]$

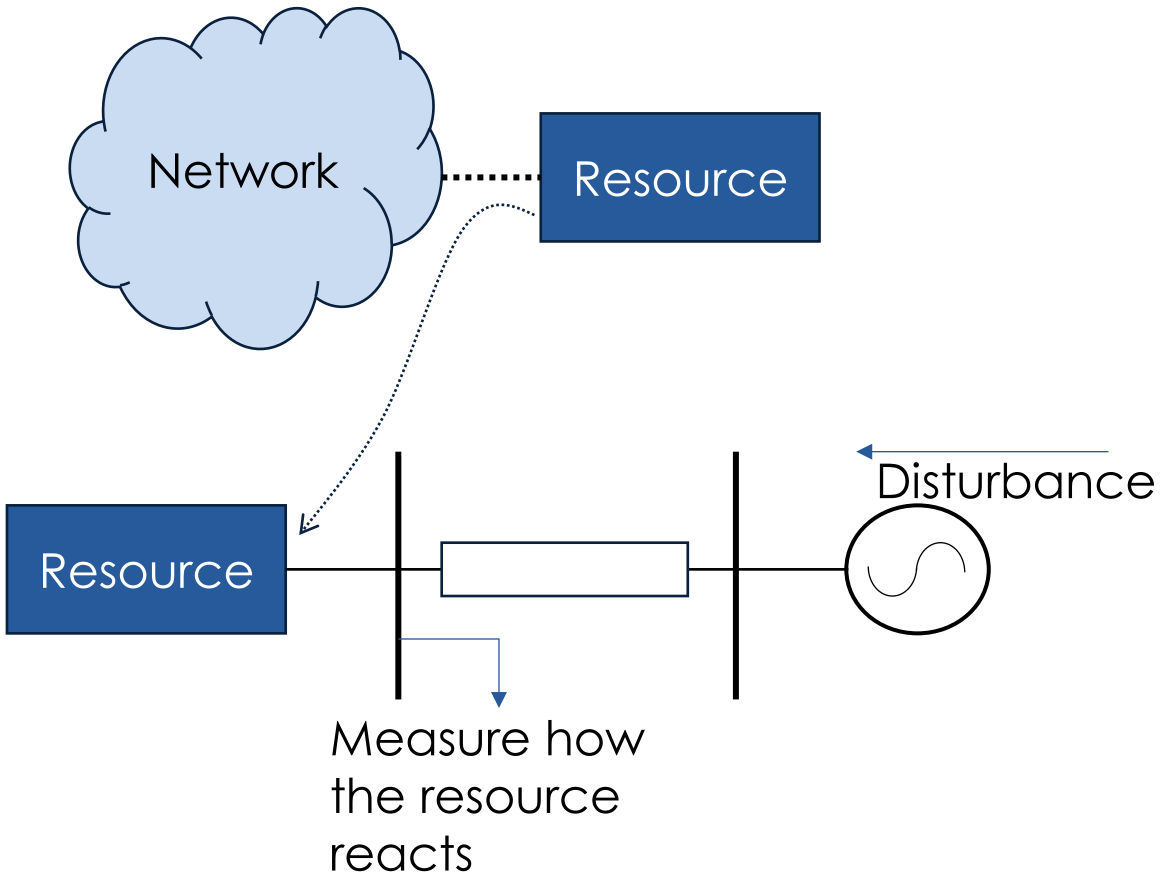
Provision of Services by an Individual Resource

- Multiple resources including IBRs, synchronous generators and other devices act together to provide different (active power, reactive power, etc.) services
- Can we get an idea of how a device will respond in a dynamic simulation? One approach can be analyzing the model's parameters.
- But, the device model may contain different flags/settings and it may be a DLL model – analysis based on just the parameters may require a lot of effort and may be inaccurate
- Another approach: subject the resource to different disturbances/tests to get an idea about its performance and how it might contribute to different services



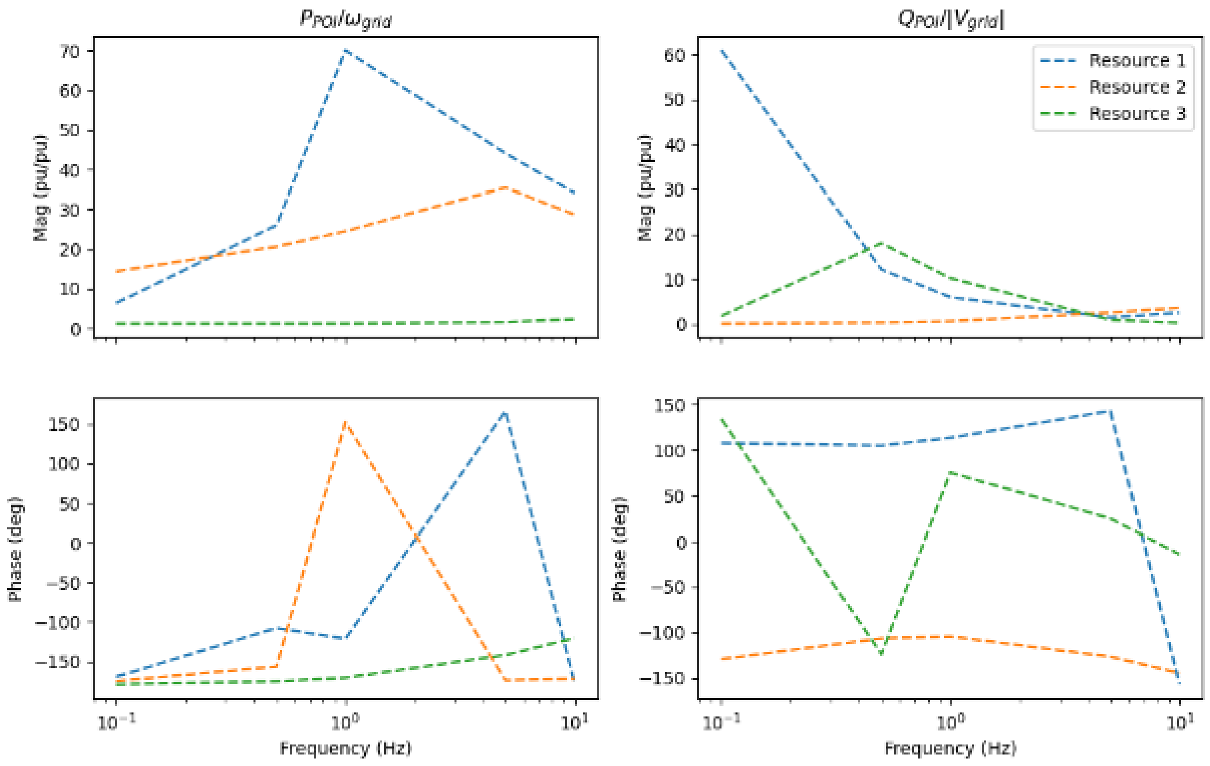
Preparing the Individual Resource for the Tests

1. Load the powerflow case
2. Identify the resource point of interconnection (POI) and disconnect any lines/transformers at the POI connecting the resource to the rest of the network.
3. Add the SMIB setup to the case and connect it to the POI.
4. Put the rest of the network out of service for faster simulation.
5. Load the dynamic model and data
6. Add appropriate disturbance – time domain and frequency domain characterization



Resource Characterization – Frequency Domain

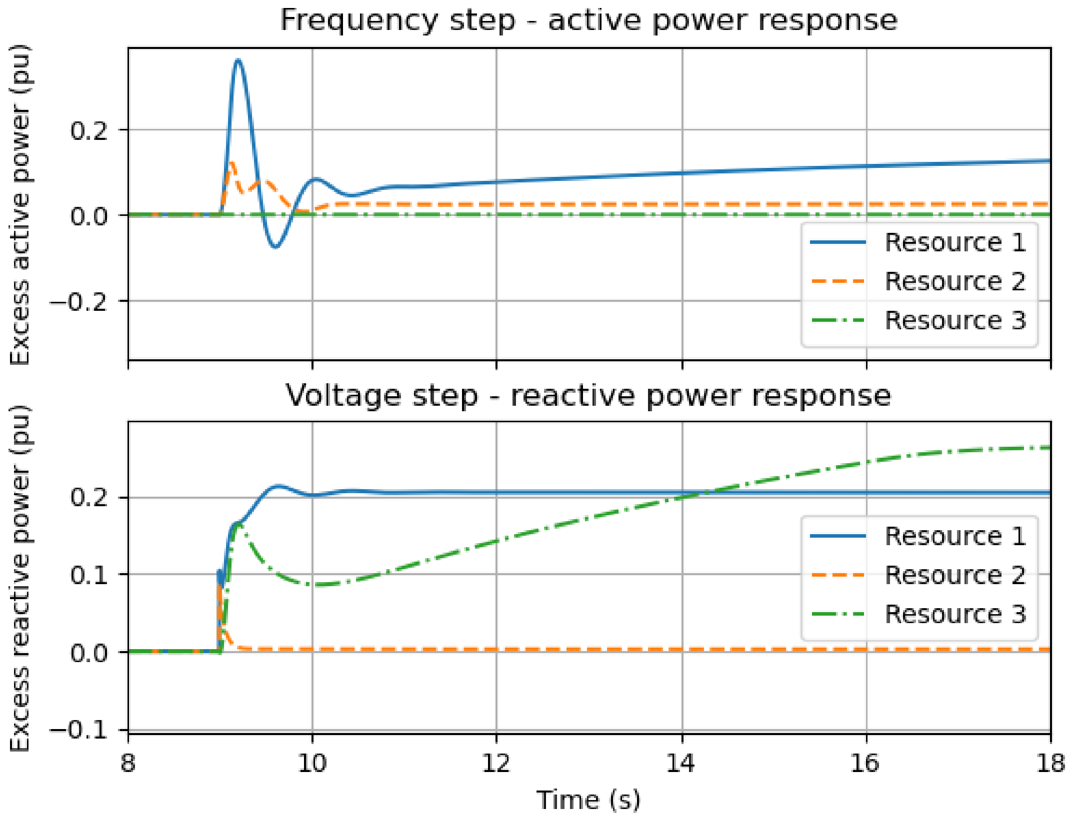
- Small signal frequency domain injection in grid voltage magnitude and frequency, and measure response in active and reactive power at that frequency
- Chosen frequencies to estimate responses in different timeframes: 0.1 Hz (slow), 1 Hz (middle), 10 Hz (fast)



Resource 1 – SM | Resource 2 – Type 2 WTG | Resource 3 – GFL IBR

Resource Characterization – Time Domain

- Step changes in grid voltage and frequency are applied as the time domain disturbances, and changes in active and reactive powers (compared to pre-disturbance values) indicate the response of the device
- The responses in different timeframes can be estimated by looking at responses during different ‘windows’: 0-0.1s (slow), 0.1s-2s (medium), 2s-9s (fast)
- Similar behavior as indicated by the frequency domain characterization
- Additional energy supplied during a timeframe – area under the curve can yield a numerical value, useful when comparing a large number of resources



Resource 1 – SM | Resource 2 – Type 2 WTG | Resource 3 – IBR

Need for Services

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Need for Stability Services

Generation Contingencies

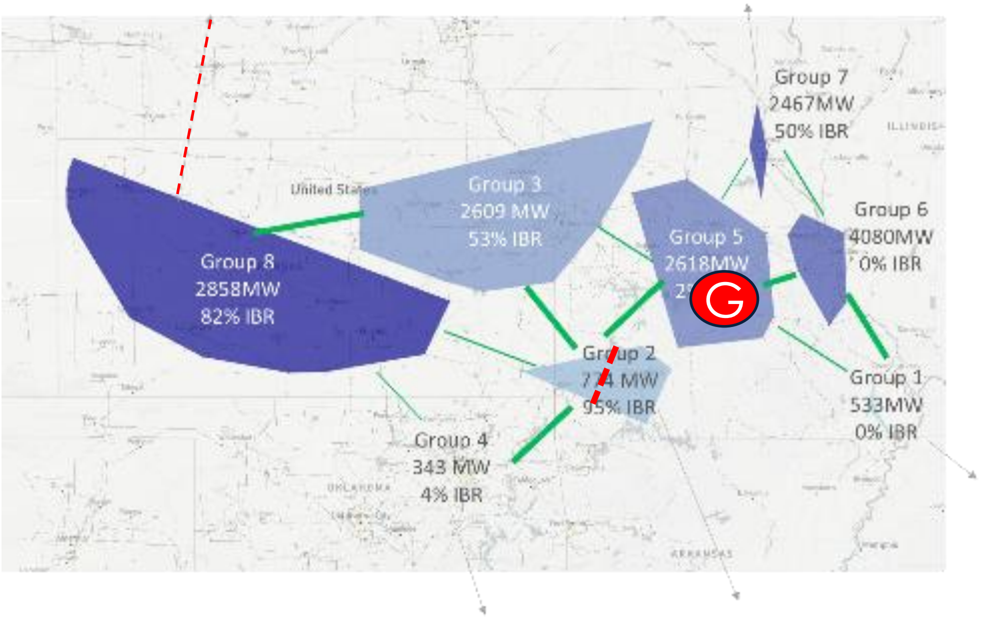
- Trip single largest generator by MW output in each "Group"
- Usually also the largest by MVA, but not always

Transmission Contingencies

- Trip single line/transformer with highest MW flow in each group
- These are usually within a group or to the external system (flows between groups are usually not high)

Monitor Dynamics

- Voltage & frequency of buses, aggregated by "Group"
- P & Q of all resources, aggregated by "Group"



Need for Stability Services

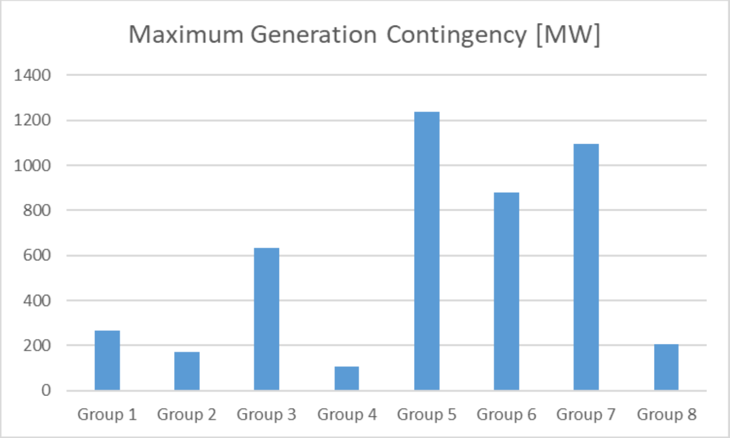
Generation Contingencies Selected, Highest MW Dispatch

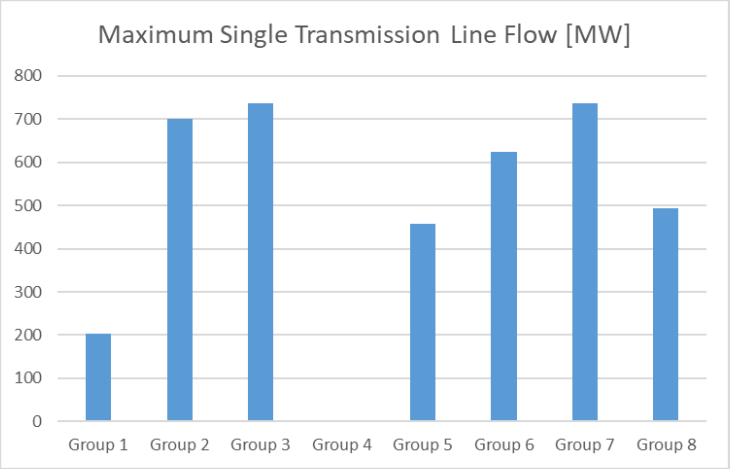
Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8
266.7	170.0	633.7	107.2	1237.6	881.0	1097.3	208.3

Transmission Contingencies Selected

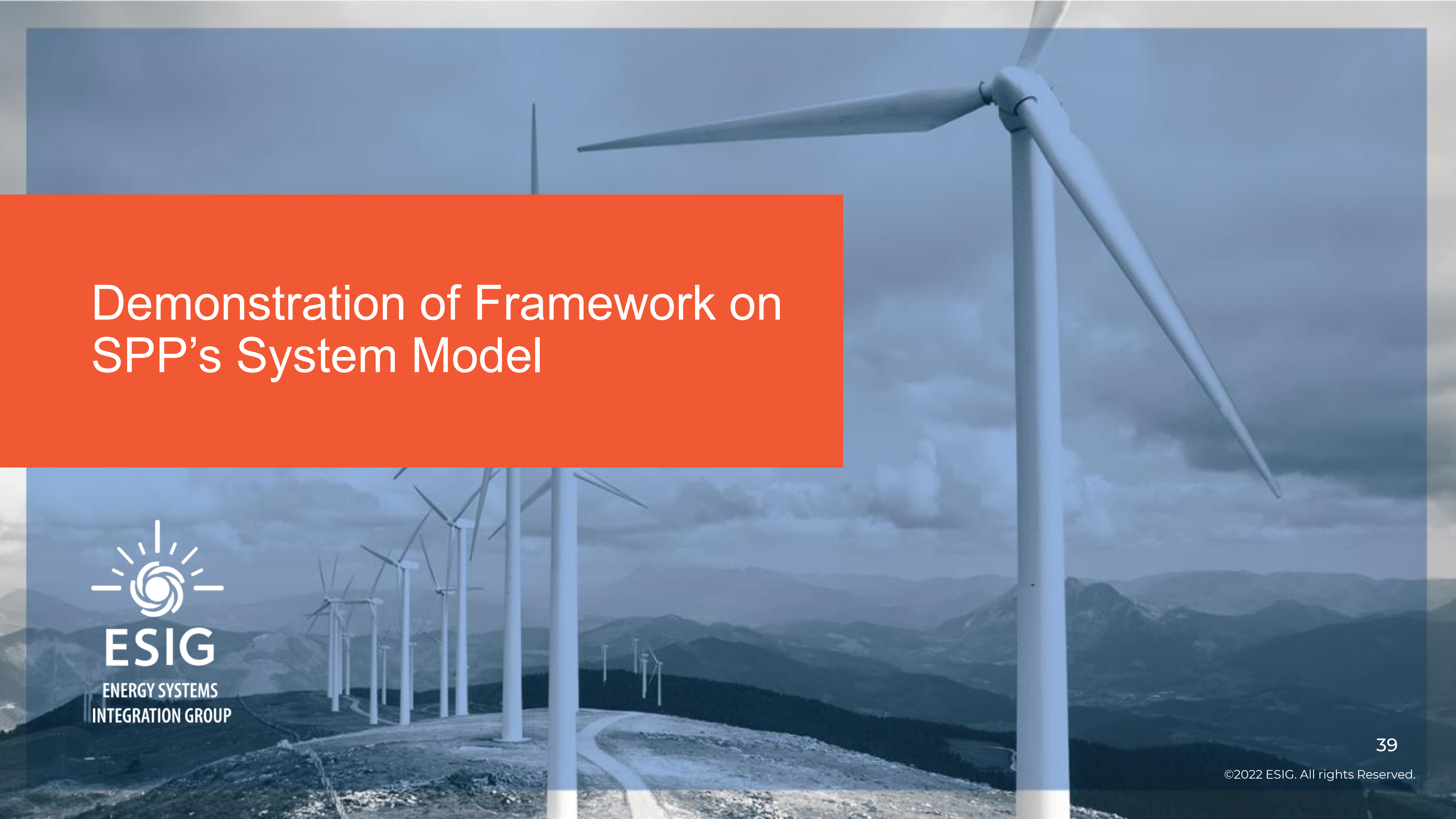
Group	kV	RateB	Xpu	Pflow [MW]	Qflow [MVAr]
Group 1	345	870	0.014	202.5	-5.7
Group 2	345	1159	0.009	700.3	-41.5
Group 3	345	1195	0.027	737.0	9.2
Group 5	345	1793	0.011	457.3	3.2
Group 6	345	1684	0.016	624.6	62.1
Group 7	345	1793	0.012	736.9	69.5
Group 8	345	1168	0.003	492.7	38.6

Note: Group 4 was particularly small and had no 345kV transmission internal to it

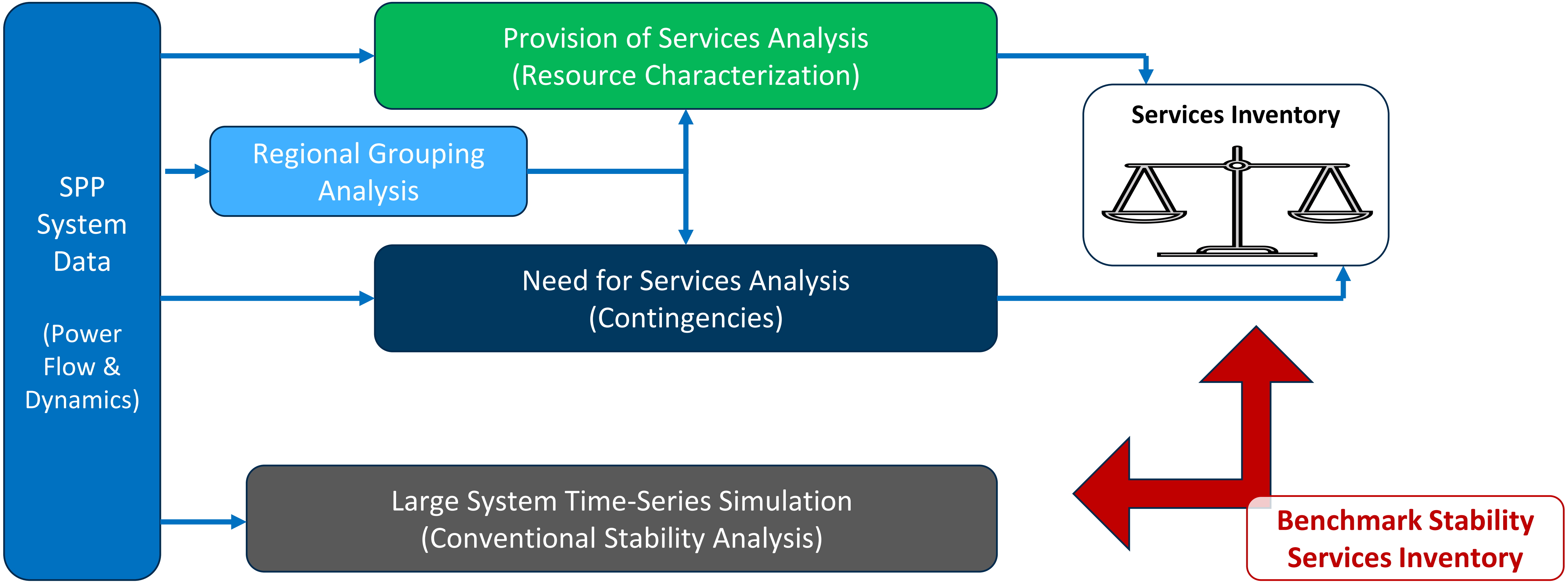




Demonstration of Framework on SPP’s System Model



How Are We Testing the Framework?



Scenario & Sensitivity Matrix

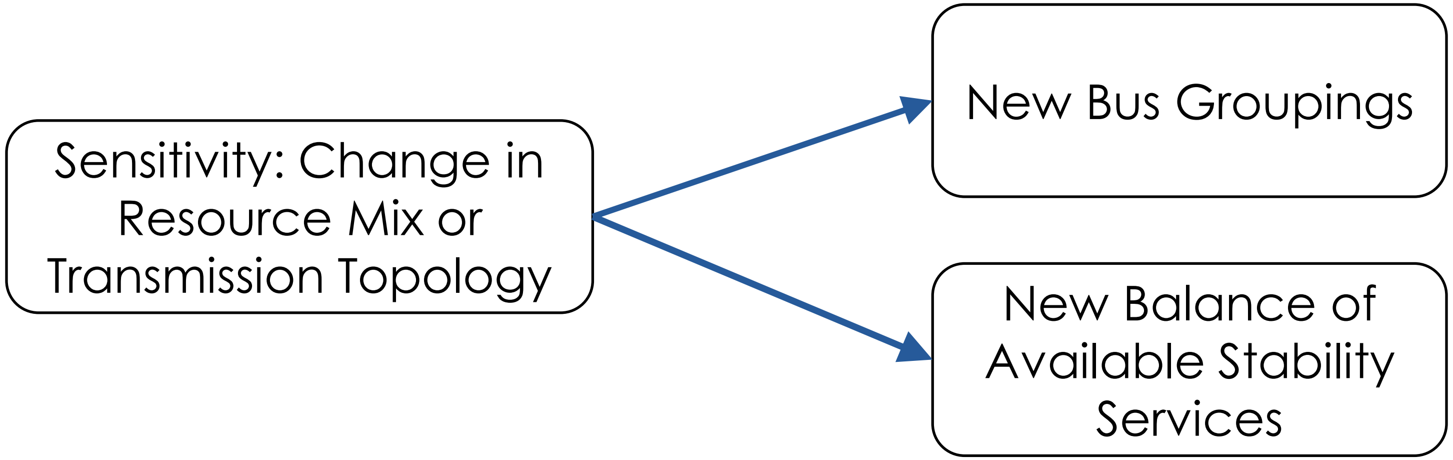
Scenario	IBR Penetration	Services Provision	Reference Case
Conventional Summer Peak Case	20% (SCR~12)	Mostly SM	SPP TPL 24S
Summer High IBR Case	40% (SCR~5)	SM + GFL	SPP TPL 24S-SENS
Light Load, High IBR (Wind) Case	60% (SCR~2)	GFL + SM	SPP TPL 24L-SENS
Very High IBR Penetration Case (GFL future build-out)	80+%	GFL + SM	Modify 24L_SENS --> sub GFL for SMs
Very High IBR Penetration Case (GFM future build-out)	80+%	GFM + SM	Modify 24L_SENS --> sub GFM for SMs
Very High IBR Penetration Case (Transmission mitigations)	80+%	GFL + SM	Modify 24L_SENS Topology --> sub GFL for SMs

Starting here as the Reference Case

Overview of Sensitivities

- High IBR, GFL-dominant sensitivity
- High IBR, GFM-dominant sensitivity
- In the future, new transmission sensitivity…

A change in resource mix or transmission impacts the balance of services as well as the relevant stability boundaries (bus groupings) within the power system



Setting Up Sensitivity Cases

Determining Units for “Conversion” from SM to IBR

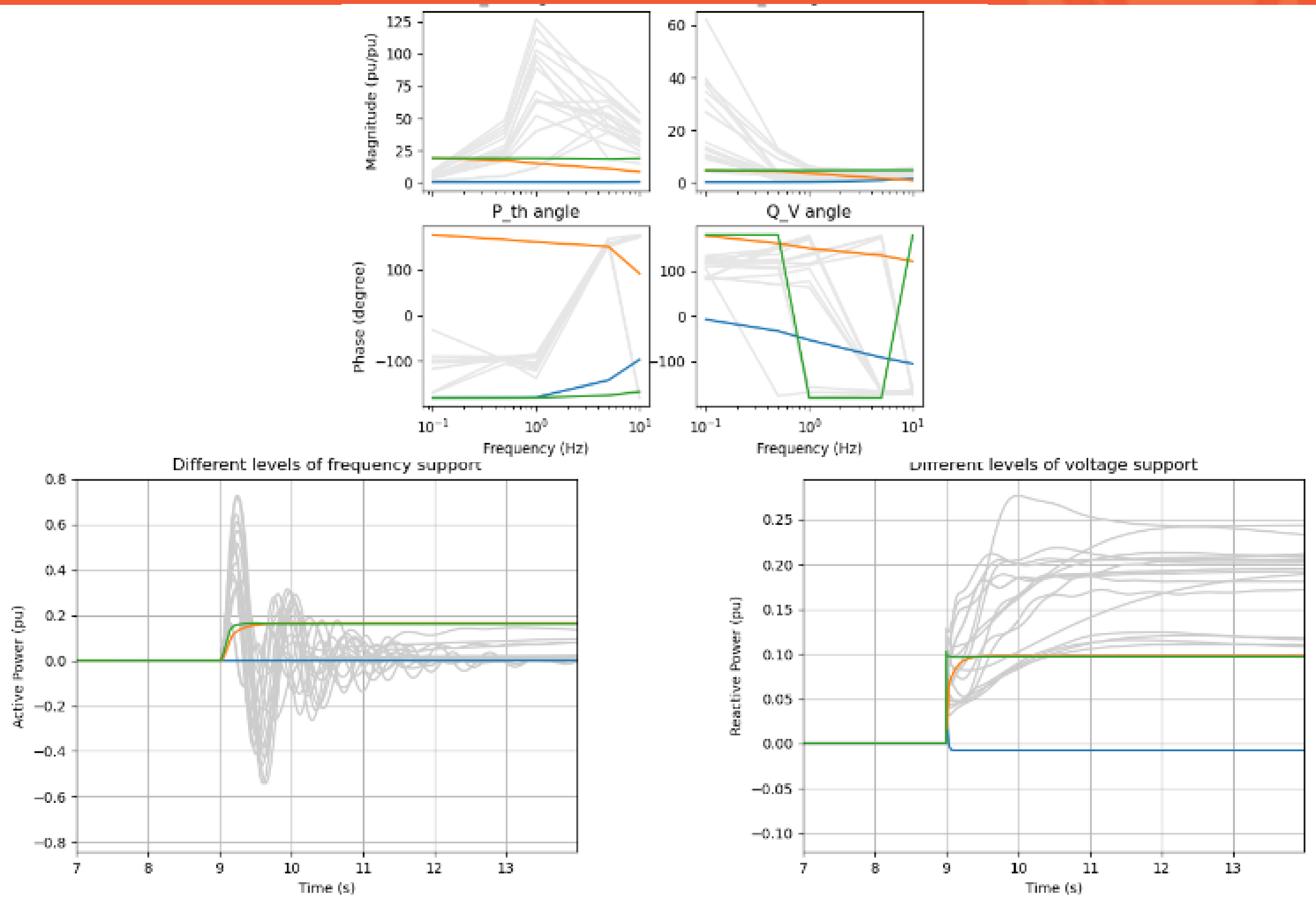
- Aimed for ~80% IBR penetration by active power generation
- Identified **18** SM units for “conversion” to IBR
- Only the dynamic models were changed
- Topology, commitment, and dispatch were unchanged for an “apples-apples” comparison with the reference case

	Total Online Pgen	IBR MW Pgen		% IBR Penetration by Pgen		Change in % IBR Penetration by Pgen
		Initial	New	Initial	New	
Group 1	533	0	267	0.0	50.0	50.0
Group 2	774	735	735	94.9	94.9	0.0
Group 3	2609	1379	1947	52.9	74.6	21.8
Group 4	344	15	237	4.4	68.8	64.5
Group 5	2619	66	2428	2.5	92.7	90.2
Group 6	4080	0	3320	0.0	81.4	81.4
Group 7	2401	1164	2262	48.5	94.2	45.7
Group 8	2859	2341	2341	81.9	81.9	0.0

Biggest changes to the previously SM heavy groups

Resource Characterization of Individual Resources
Replacing Synchronous Generators

- Synchronous generators replaced show a range of responses (gray) – to be replaced by IBRs providing different levels of services (colored)
- IBRs providing different levels of services are explored in later slides



Different IBR Models Used for Sensitivity Cases

- IBRs can be categorized based on the services they provide
- Three IBRs parameterizations initially considered:
  - IBR GFL Cat1 – provides minimal/no services (worst-case)
  - IBR GFL Cat3 – another GFL parameterization that provides a high level of services
  - IBR GFM – provides fast frequency and voltage services among others
- IBR GFL – uses generic renewable models (REGC/REEC/REPC)
- IBR GFM – uses generic grid forming inverter model (GNRGFM)
- GFL Cat1 and GFM are used to represent the two extremes in all sensitivities

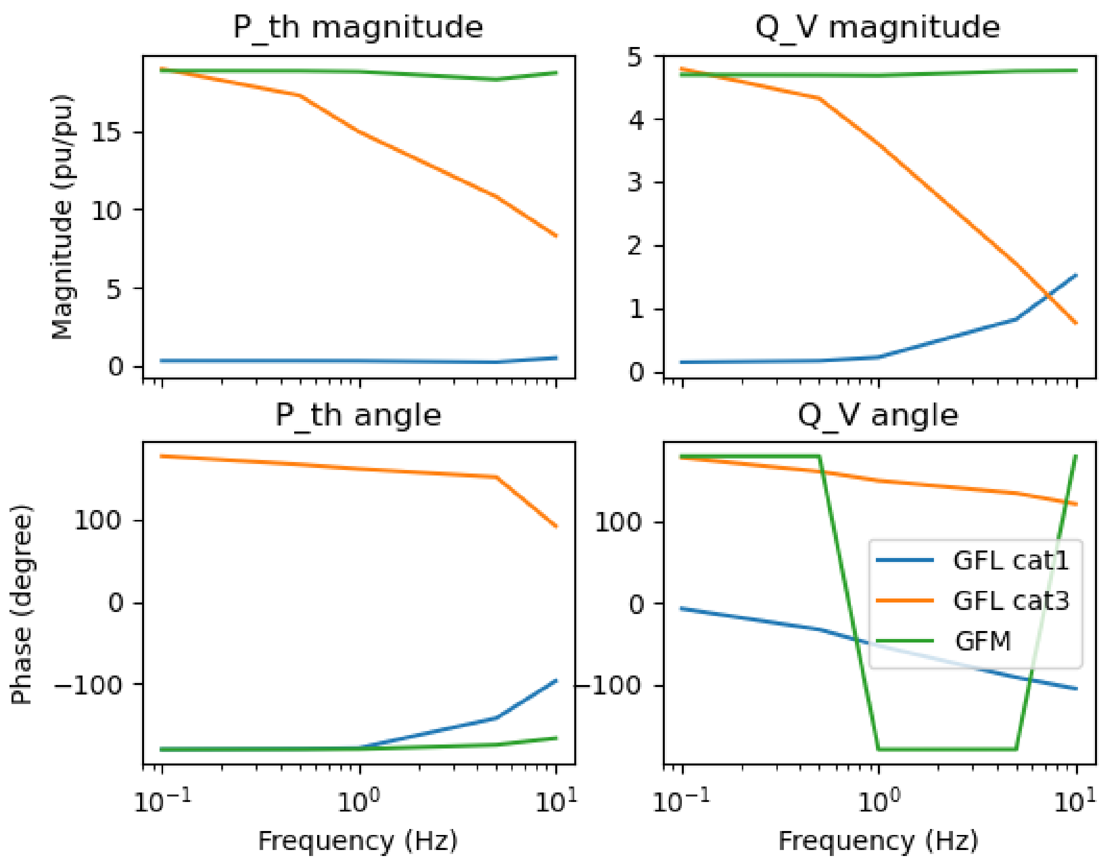
GNRGFM source: Generic Grid Forming Inverter Model Version 1.0: For PSS/E Versions 33 and 34. EPRI, Palo Alto, CA: 2024. 3002030987

Different IBR Models Used for Sensitivity Cases

- Services provided – depend on what functionalities are activated in the model as well as on control parameters chosen
- Different control parameters may be appropriate for different systems
- GFL Cat1 – constant active power, constant reactive power controls (very pessimistic)
  - Uses electric control (REEC) model following the active and reactive power command
- GFL Cat3 – relatively fast voltage and frequency support
  - Uses plant (REPC) and electric (REEC) control models providing voltage and frequency support
- GFM – different control modes possible for grid forming inverters
  - Uses droop-based single-loop control (GNRGFM)
  - GNRGFM model uses similar control structure to other generic GFM models (REGFM_A1 and REGFM_B1)

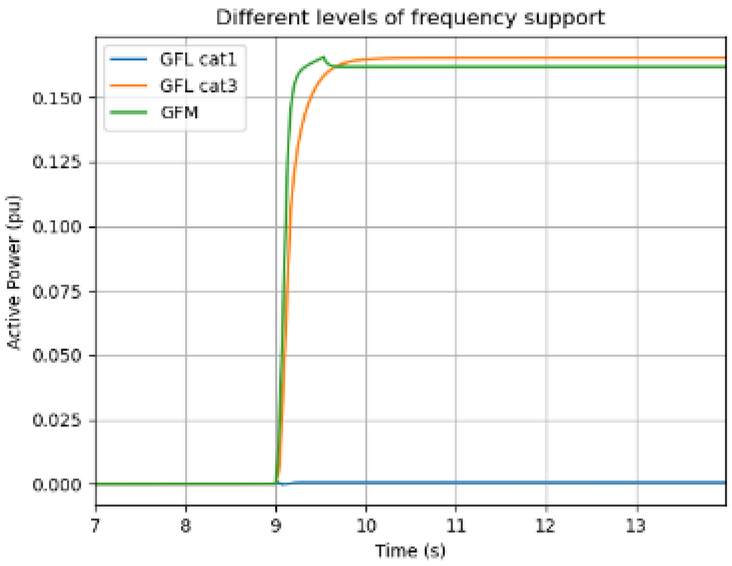
Different IBR Parameterizations – Frequency Domain Characterization

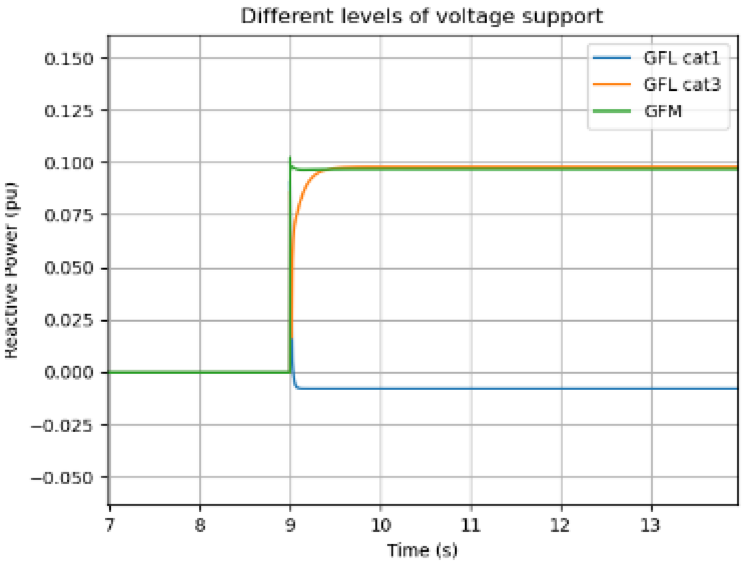
- GFL Cat1 – provides minimal/no support
- GFL Cat3 and GFM provide active power/frequency and reactive power/voltage support
- For the slower frequencies, same droop coefficient cause similar responses, but in the faster region there are differences – related differences in faster controls and tuning
- Factors such as deadbands and size of the frequency domain disturbance chosen may also play a role



Different IBR Parameterizations – Time Domain Characterization

- GFL Cat1 – provides minimal/no support
- GFL Cat3 and GFM provide active power/frequency and reactive power/voltage support
- In the initial ~0.5s, there are differences in GFL cat3 and GFM response, after that the responses are similar due to similar droop coefficients
- Factors such as deadbands also play a role



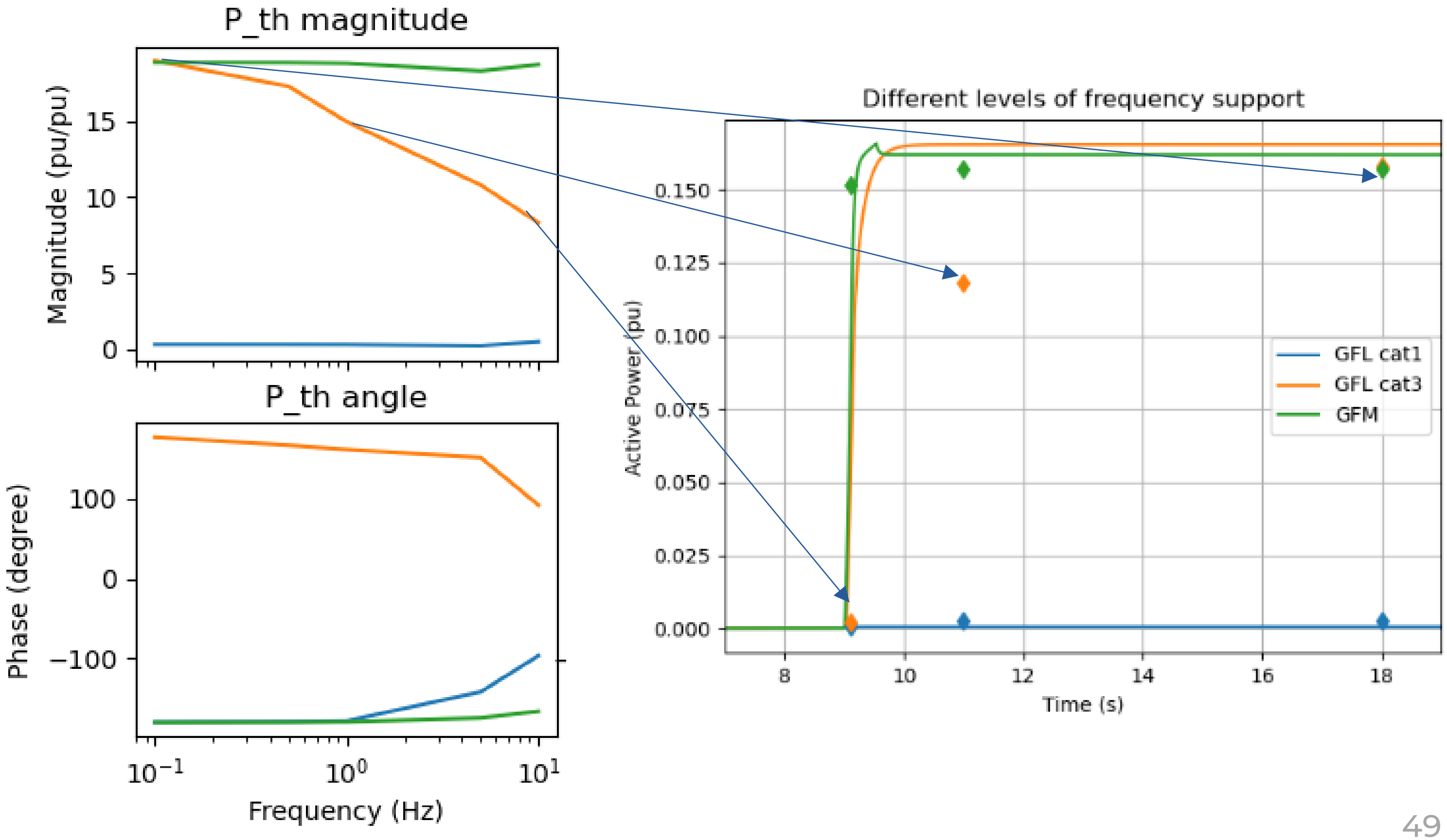


How do the Time Domain and Frequency Domain Characterizations Compare?

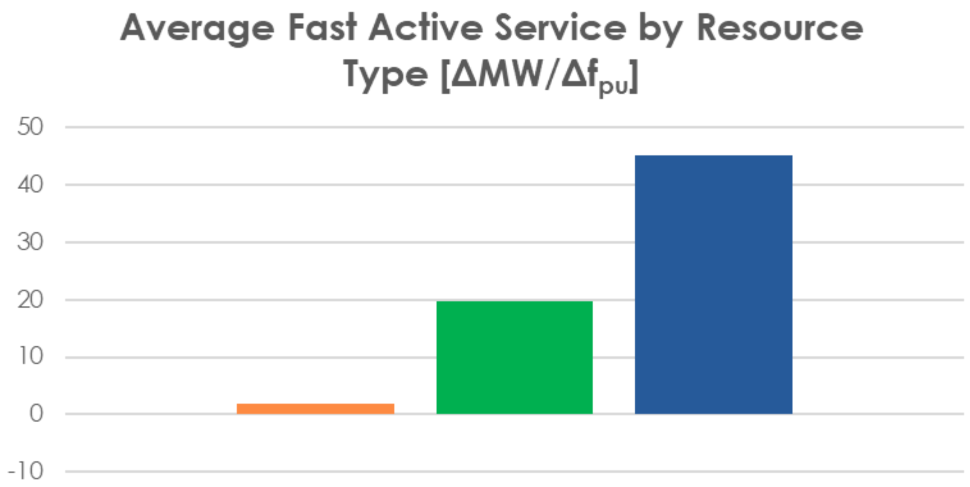
- Response in time domain over 0-0.1s (fast), 0.1-2.0s (medium), 2-9s (slow)
- The following is calculated for 10 Hz (fast), 1 Hz (medium) and 0.1 Hz (slow) frequency domain response:

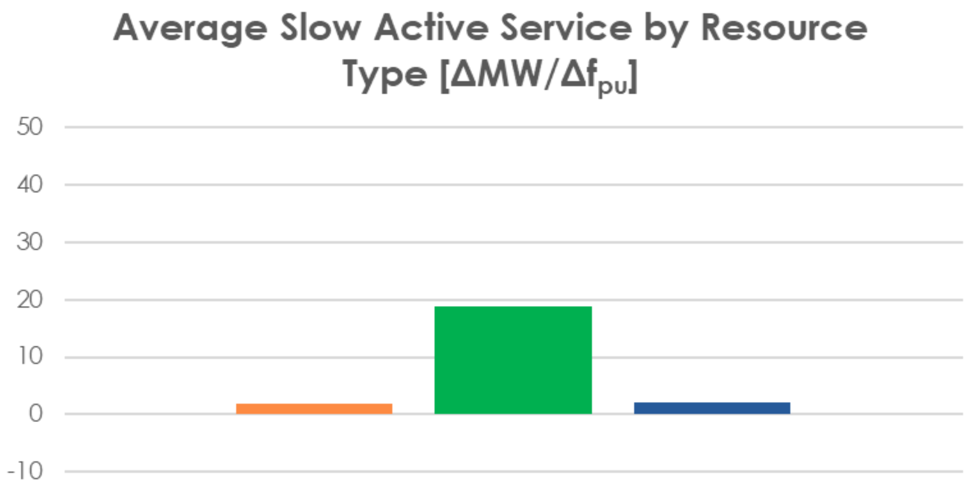
$\Delta P \approx (\text{magnitude} * \cos(\text{phase})) * \Delta f$

- Some differences still exists, potential reasons:
  - Differences in disturbance – sinusoidal at a single frequency vs step
  - Nonlinearities such as delays and deadbands



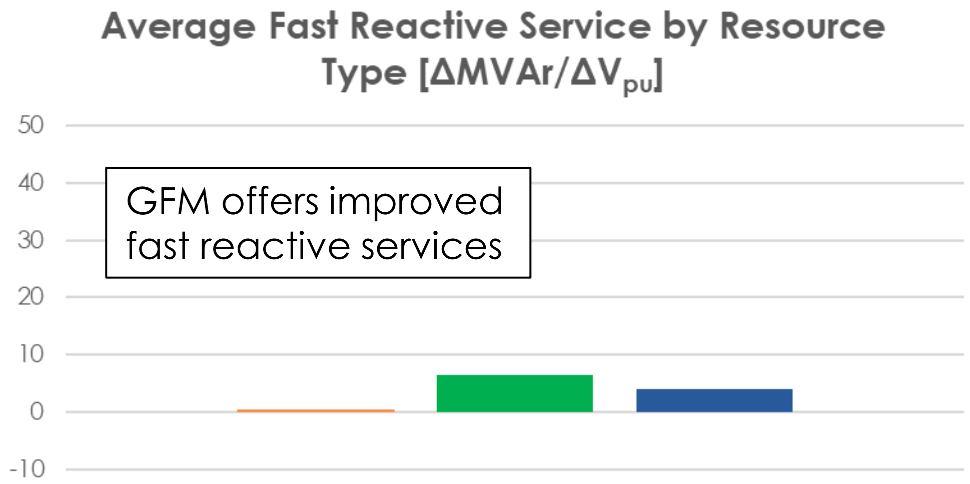
Service Provision by Resource Type

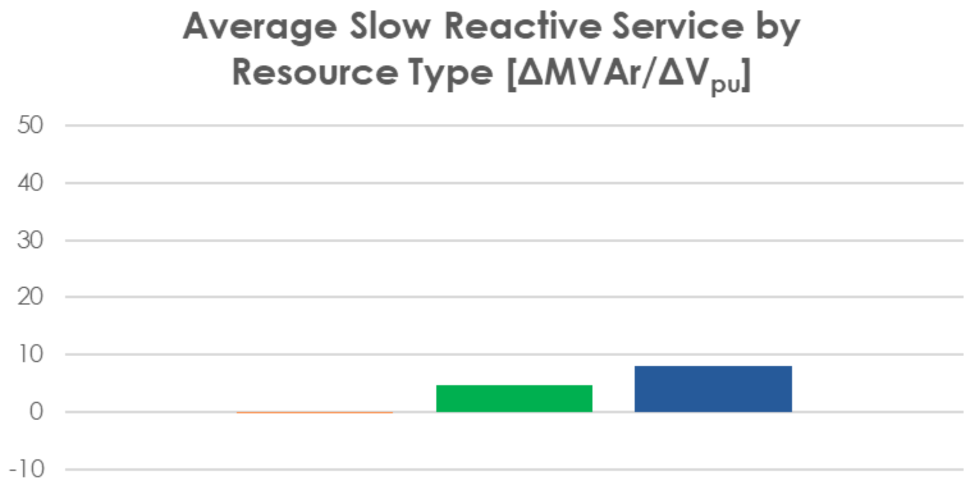




All plots in per-unit weighted by generator MVA

GFLCat1
GFM
SM





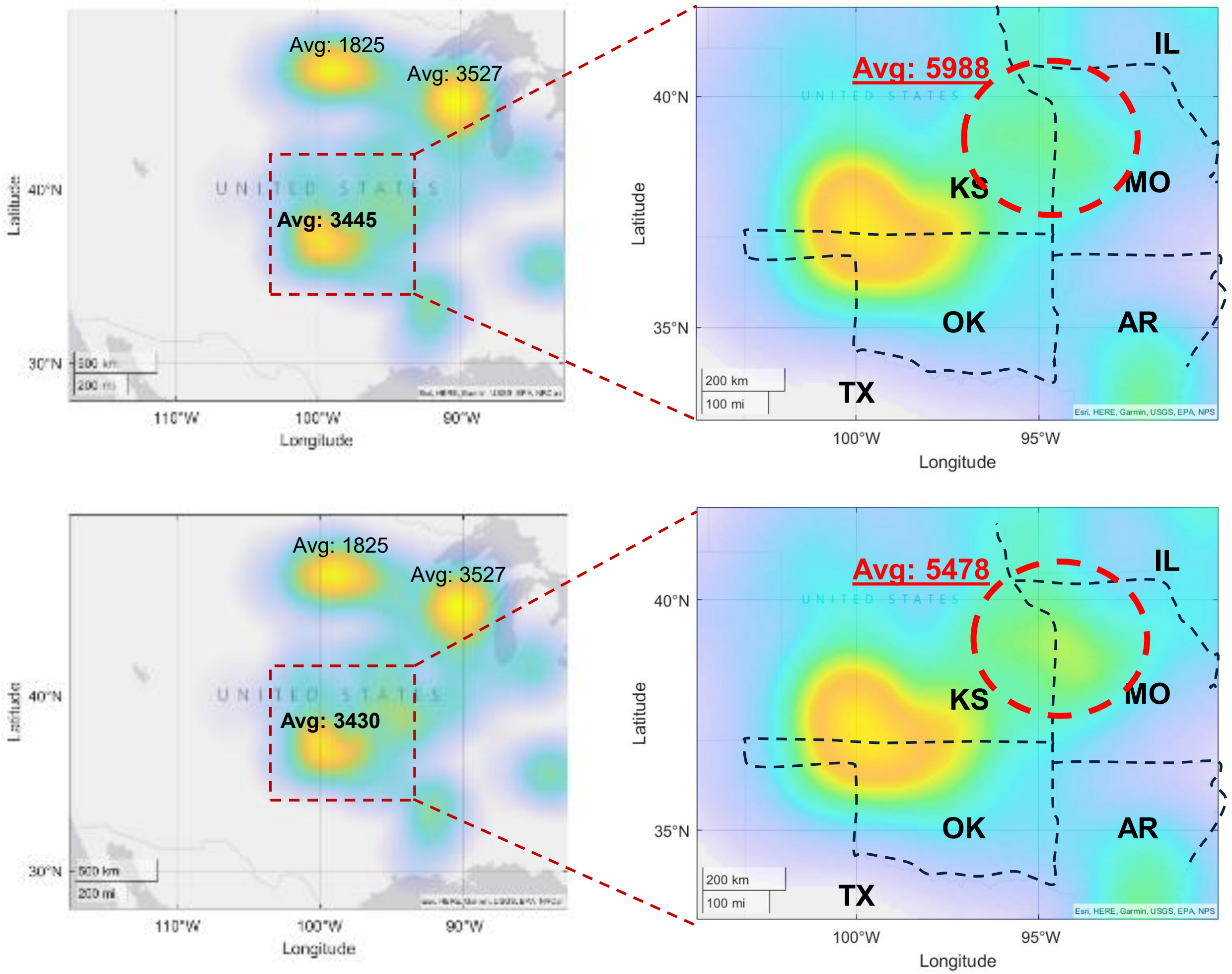
No headroom limits applied!

Grid Strength Assessment

Sensitivity Case S0 - 345 kV Short Circuit MVA Scan

Base Case

S0 – IBR



Base Case vs. S0 IBR Dominant Case (Increased IBR Presence in MO, IL, KS)

- The 'IBR Case' has 18 synchronous generators replaced with IBRs in MO, IL, KS.
- The reduced presence of synchronous generators in MO/IL/KS caused the short-circuit capacity in the region to decrease.
- This is indicated by the area in the red dash circle, in which the yellow region brightens indicating an increased risk in grid strength. The average short circuit MVA in the region reduced from 5988 MVA to 5478 MVA.

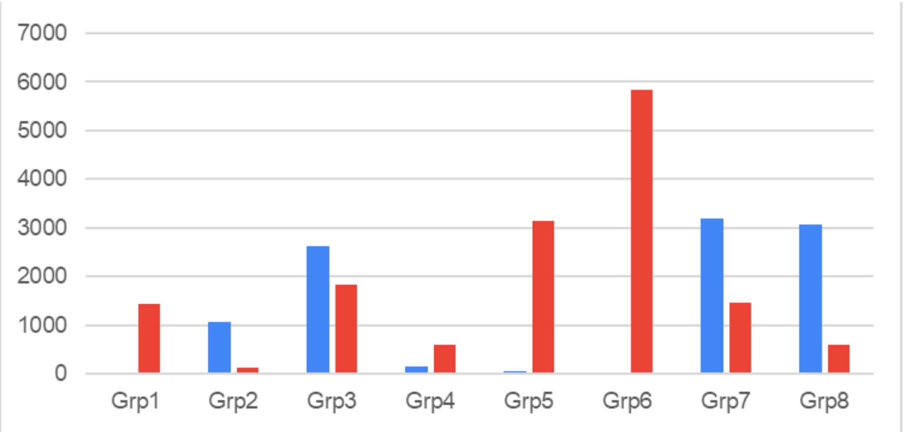
Synchronous Machine Dominant Case

ENERGY SYSTEMS INTEGRATION GROUP

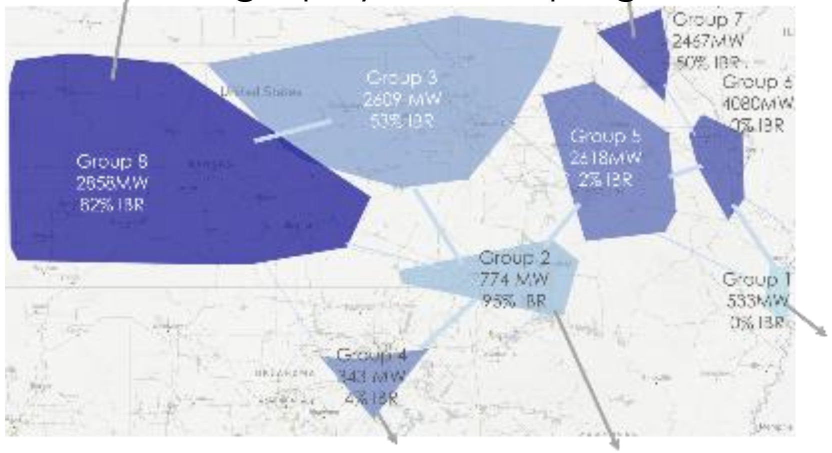
Inventory of Services – Provisions

SM Dominant Case

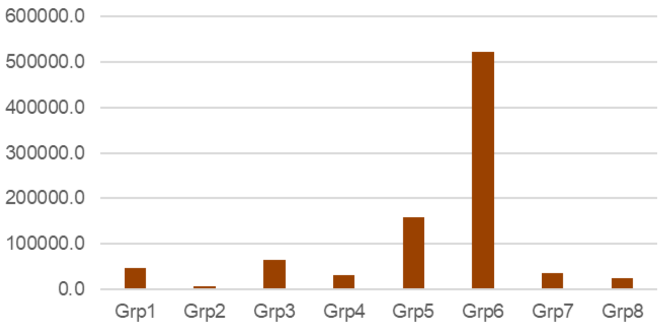
MVA of Online Resources [SM, IBR]



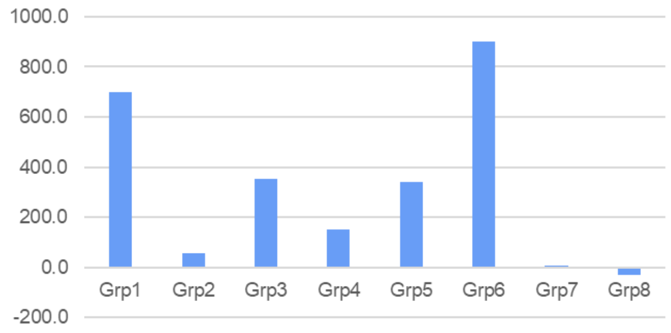
Geography of Groupings



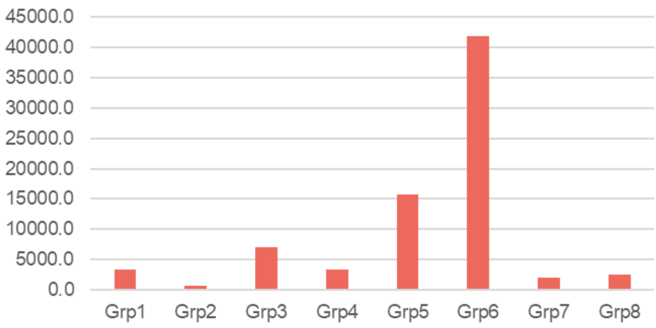
Fast Active Power [ΔMW/Δf$_{pu}$]



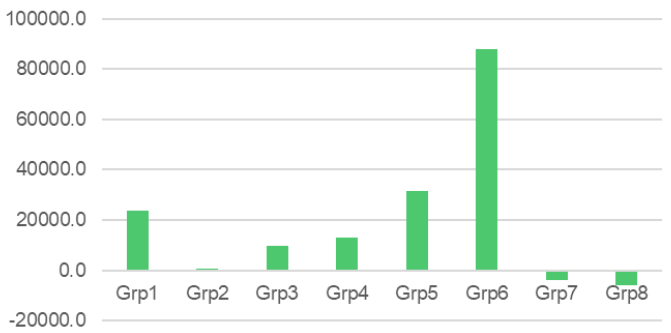
Slow Active Power [ΔMW/Δf$_{pu}$]*



Fast Reactive Power [ΔMVAr/ΔV$_{pu}$]



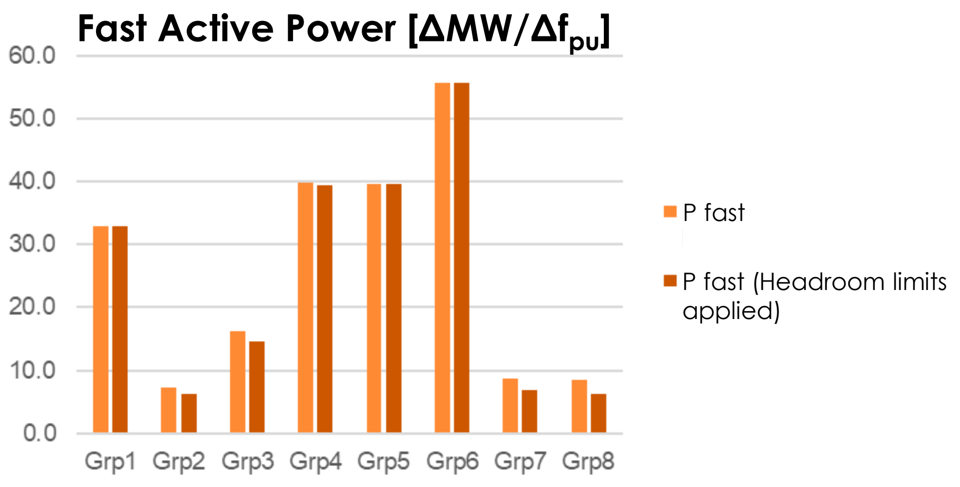
Slow Reactive Power [ΔMVAr/ΔV$_{pu}$]*

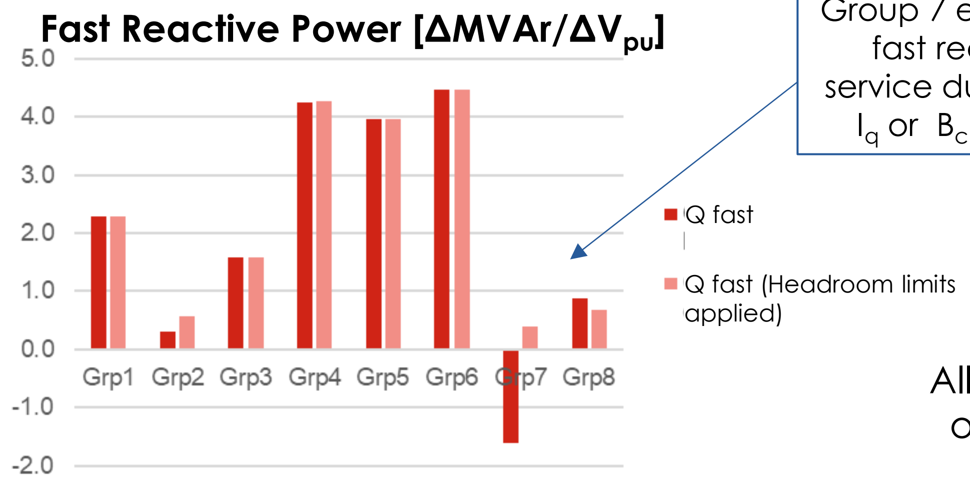


*Slow services are limited by headroom

Headroom Limitations Applied

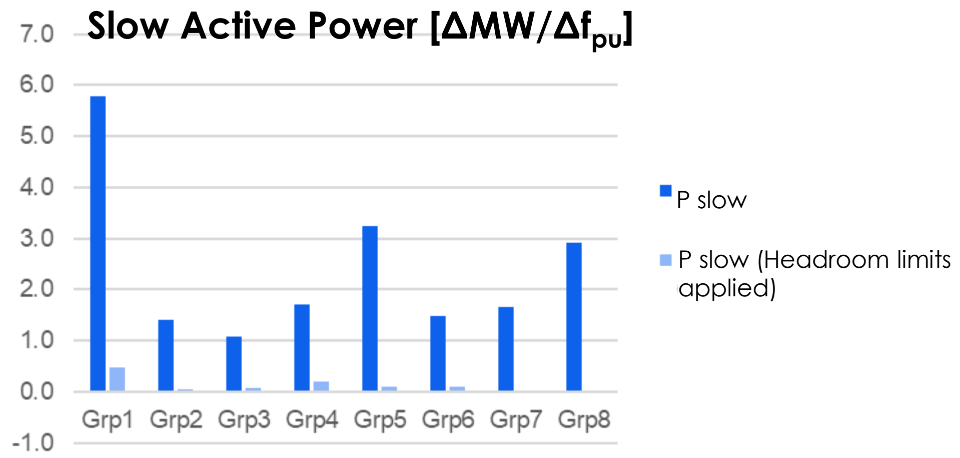
SM Dominant Case

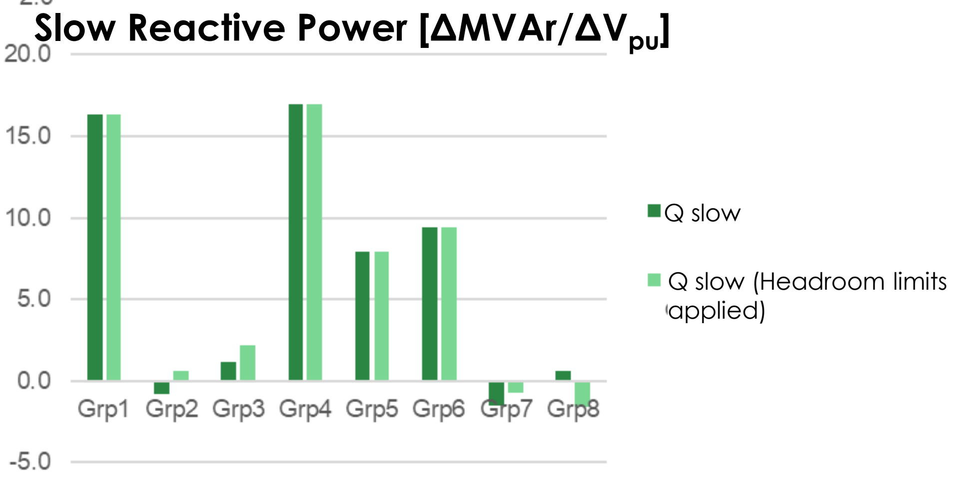




Group 7 exhibits negative fast reactive power service due to a constant I_q or B_c characteristic

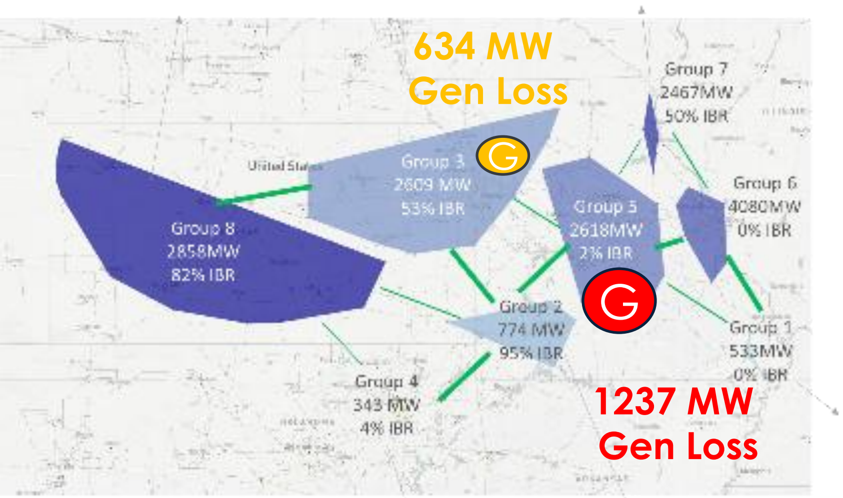
All plots in per-unit on group online MVA base

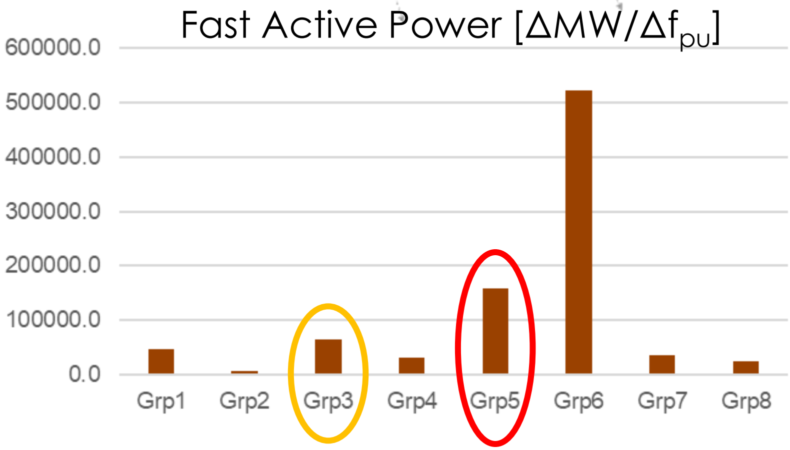




Benchmarking: Active Power Services

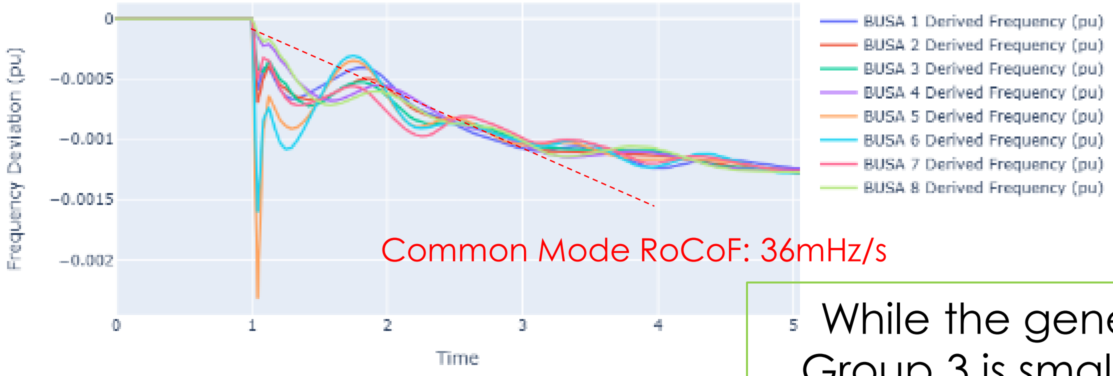
SM Dominant Case





Frequency Deviation

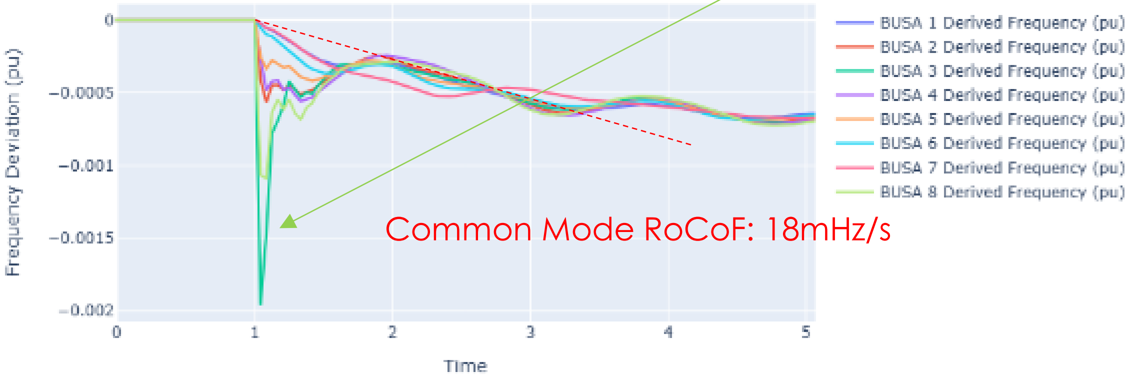
1237 MW Generation Loss



While the generation lost in Group 3 is smaller, with fewer services in the region the local stress is more pronounced

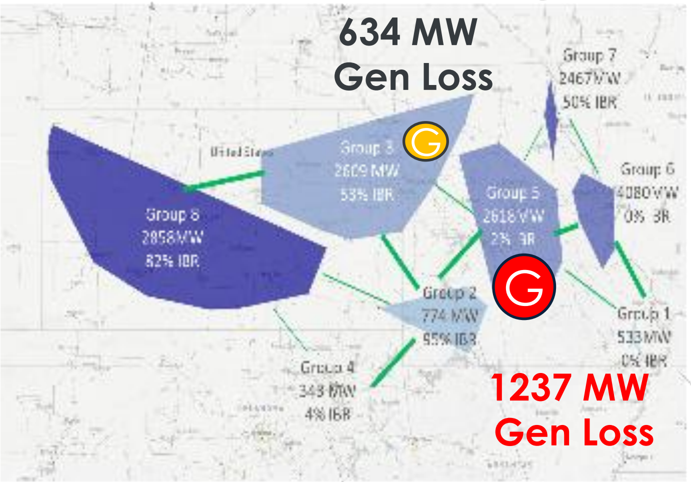
Frequency Deviation

634 MW Generation Loss

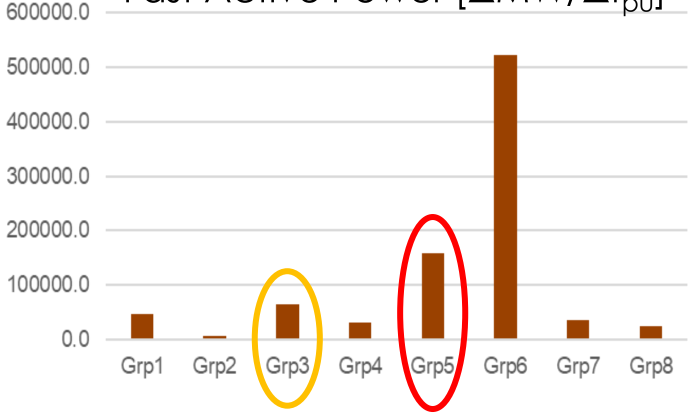


Inter-Group Support: Active Power Services

SM Dominant Case

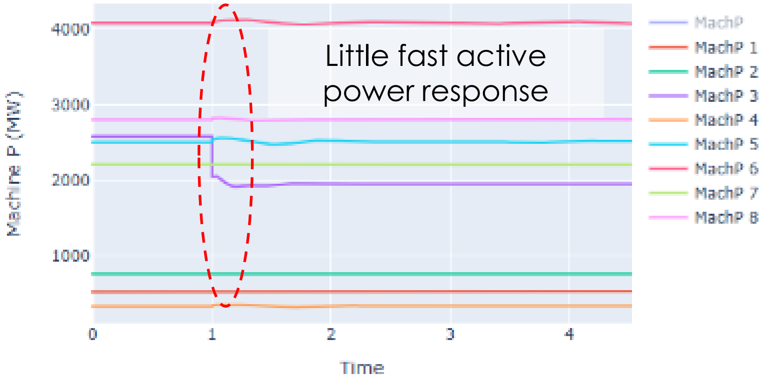


Fast Active Power [$\Delta MW/\Delta f_{pu}$]



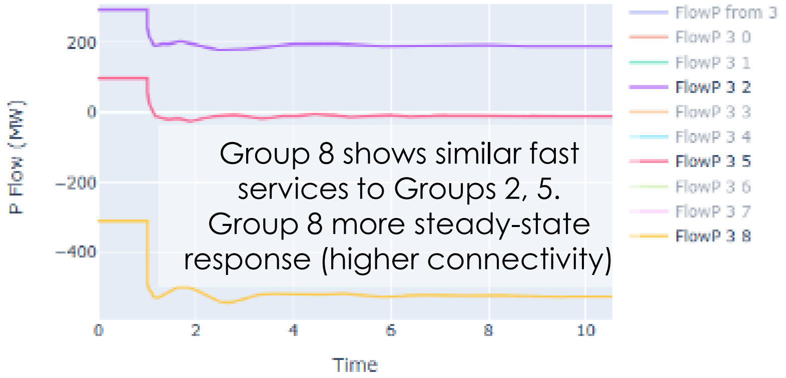
Resource Active Power, By Group

Loss of 634 MW



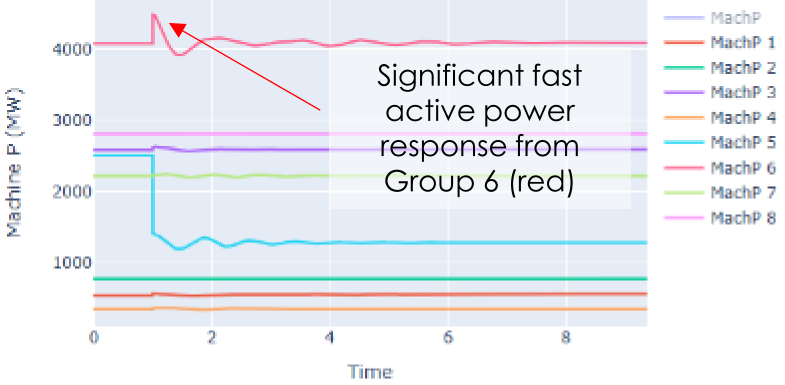
Active Power Transfer, By Group

Loss of 634 MW



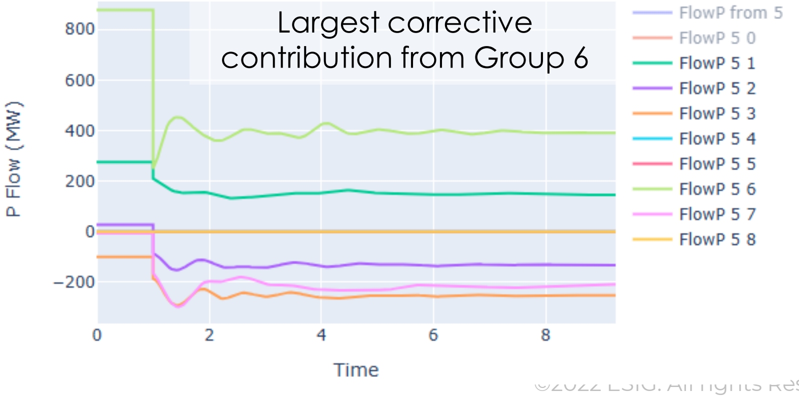
Resource Active Power, By Group

Loss of 1237 MW

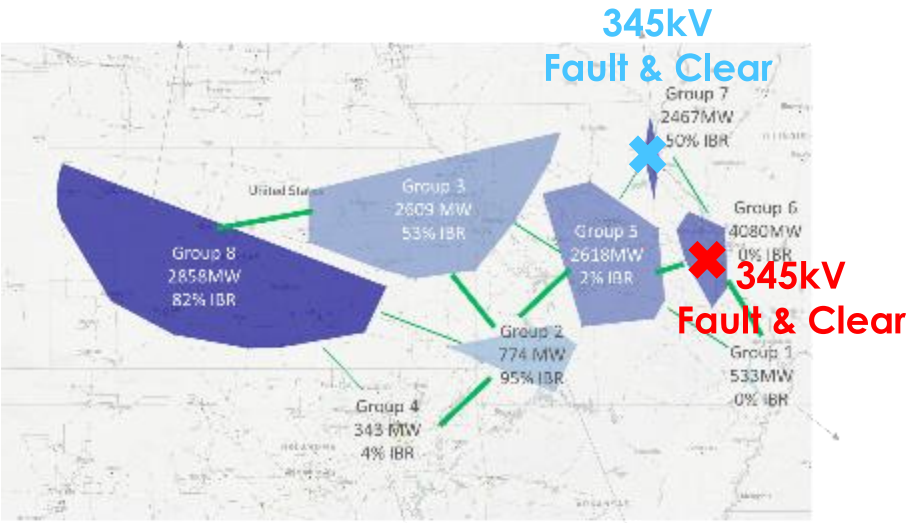


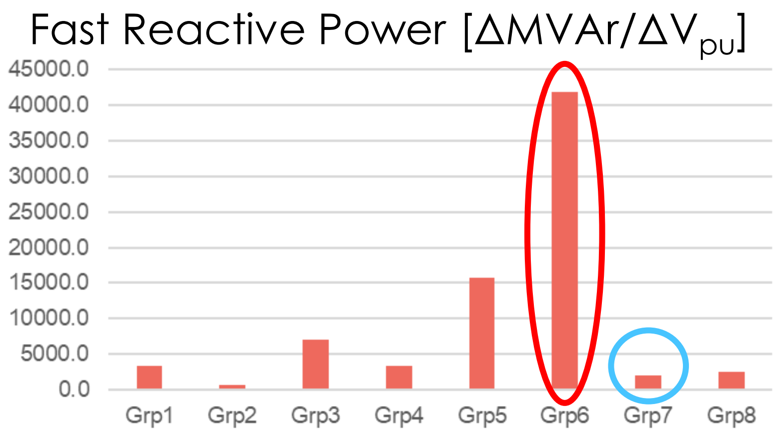
Active Power Transfer, By Group

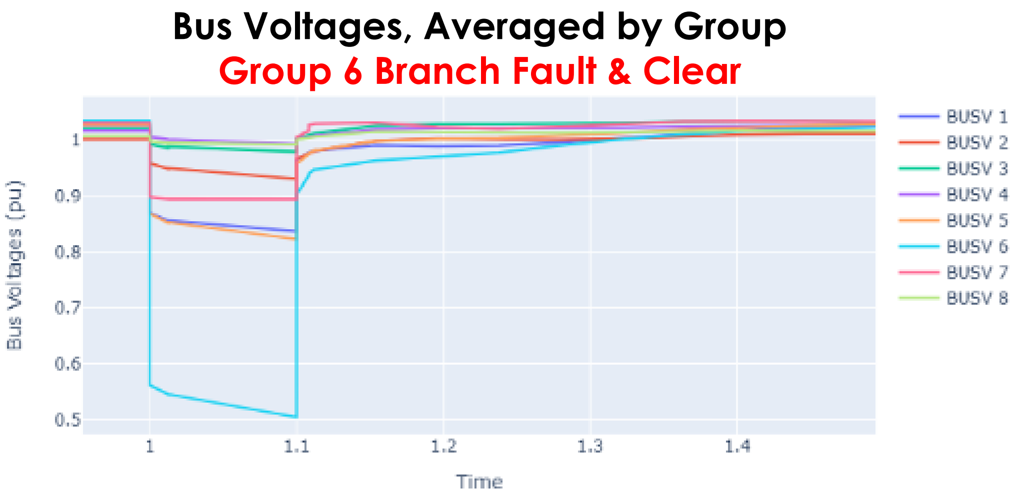
Loss of 1237 MW



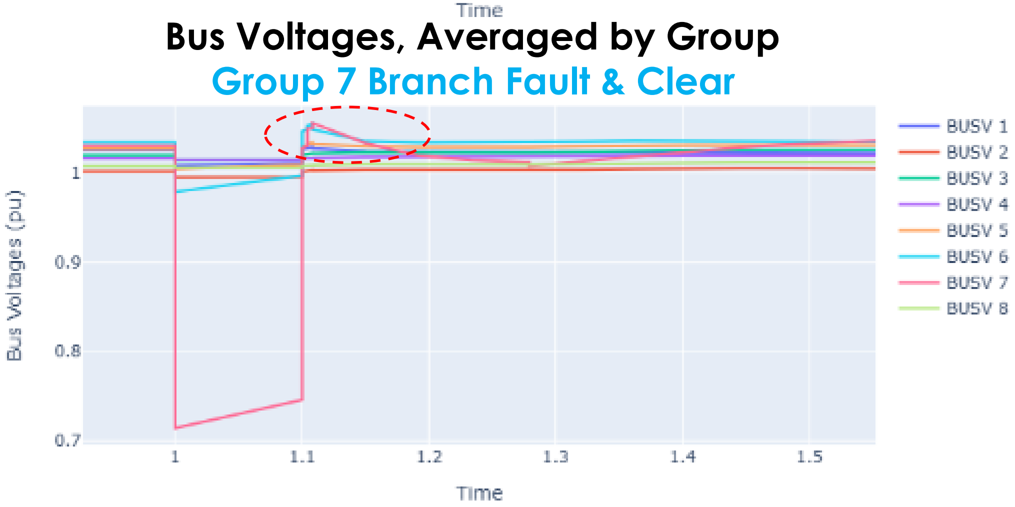
Benchmarking: Reactive Power Services
SM Dominant Case







Highly stable recovery with high levels of Reactive Services

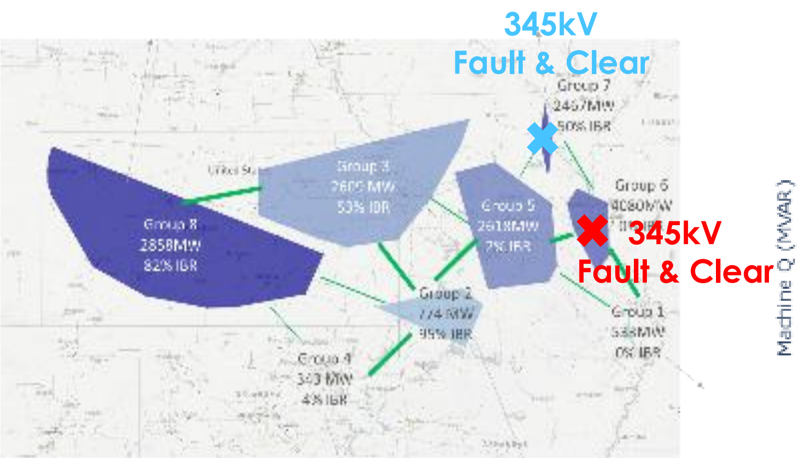


More overshoot and dynamics observed with lower Reactive Services

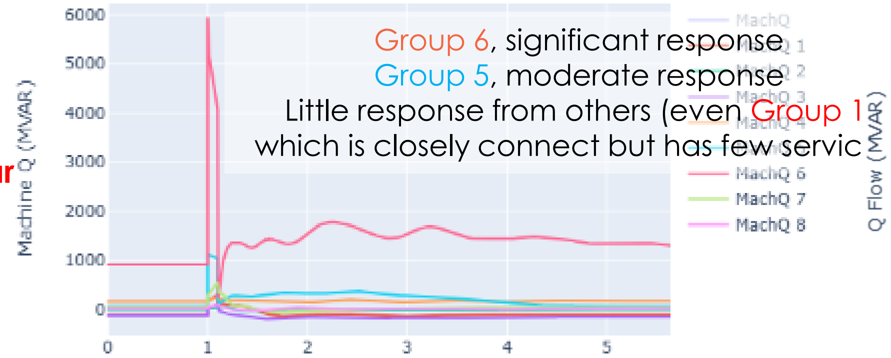
Lines were carrying 624MW (Group 6), 736 MW (Group 7)

Benchmarking: Reactive Power Services

SM Dominant Case

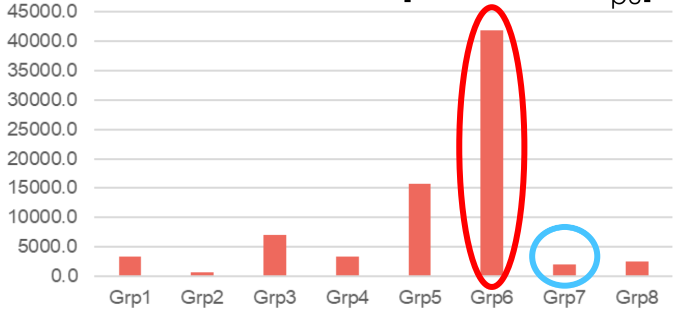


Resource Reactive Power, By Group
Group 6 Fault & Clear 345kV Line

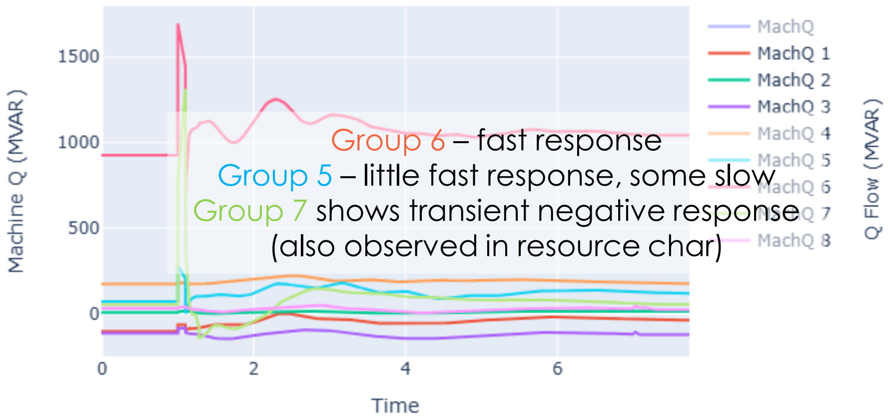


Reactive Power Transfer, By Group
Group 6 Fault & Clear 345kV Line

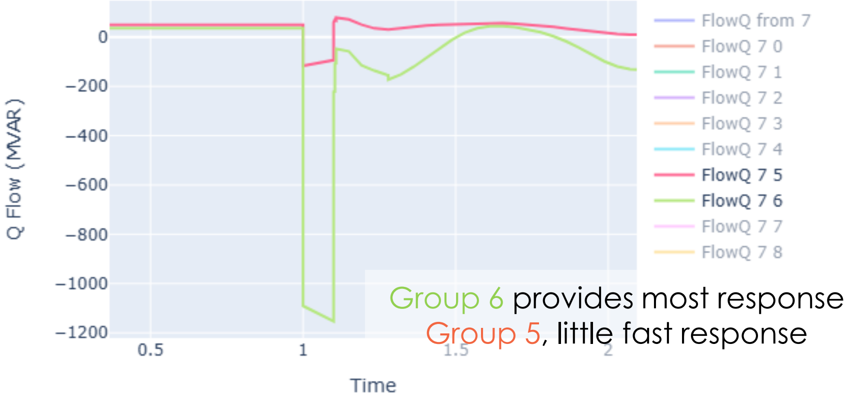
Fast Reactive Power [$\Delta MVAr/\Delta V_{pu}$]



Resource Reactive Power, By Group
Group 7 Fault & Clear 345kV Line



Reactive Power Transfer, By Group
Group 7 Fault & Clear 345kV Line

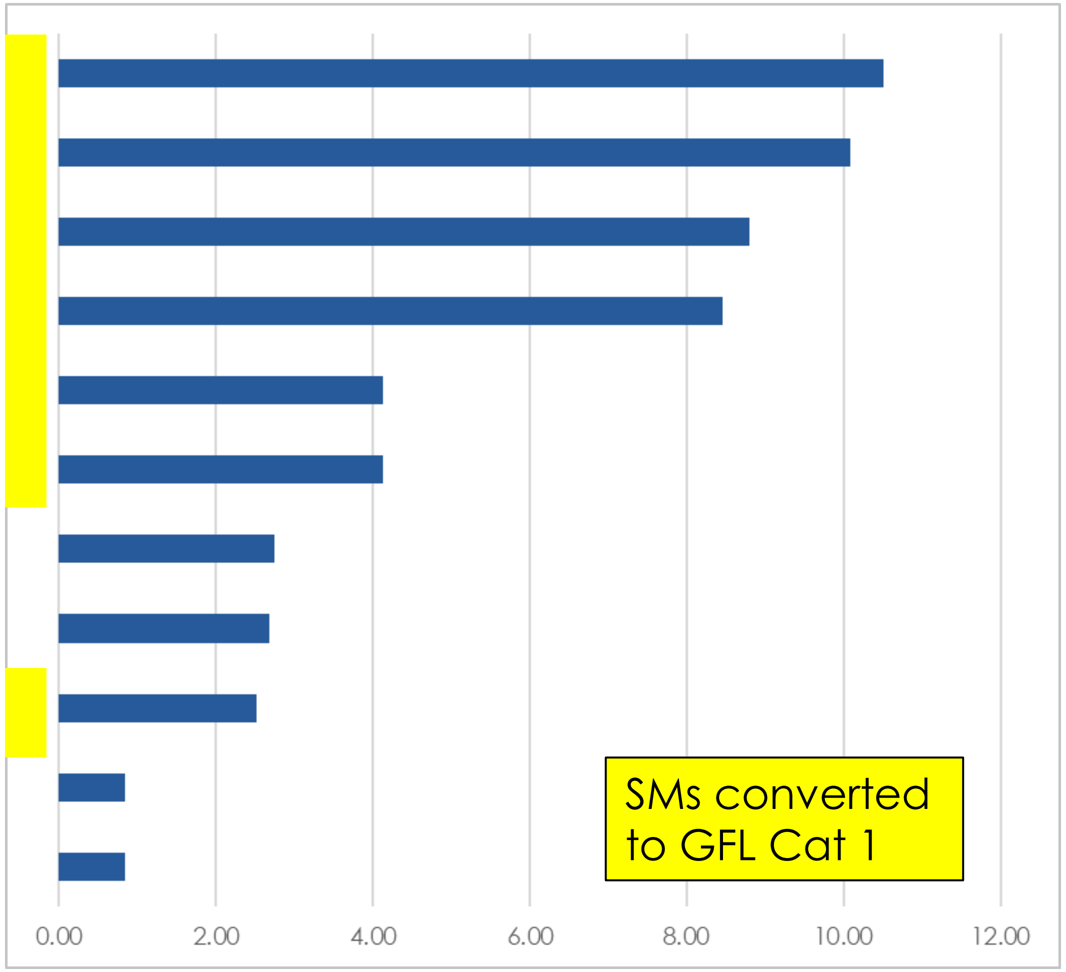


Lines were carrying 624MW (Group 6), 736 MW (Group 7)

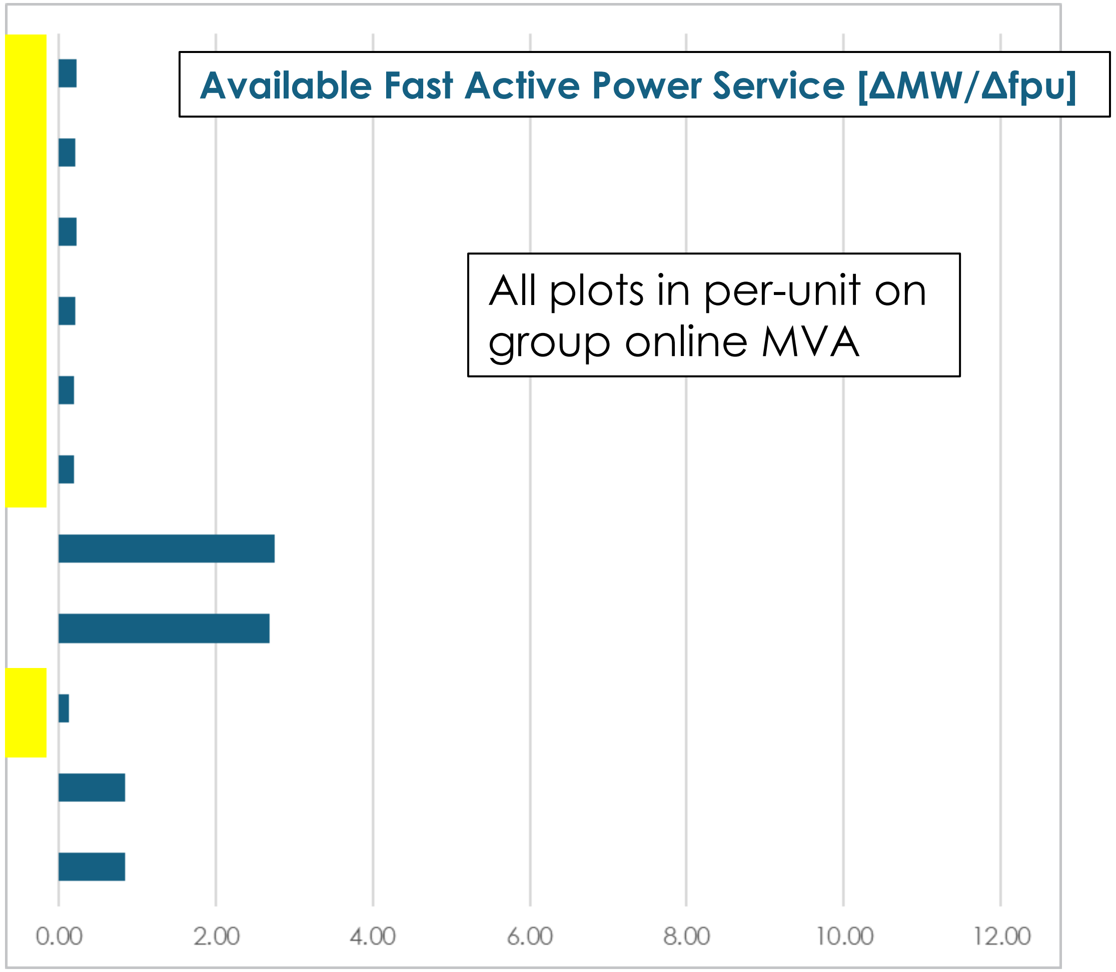
GFL-Dominant Case

(GFL Category 1)

Example: SM -> IBR Conversion in Group 6



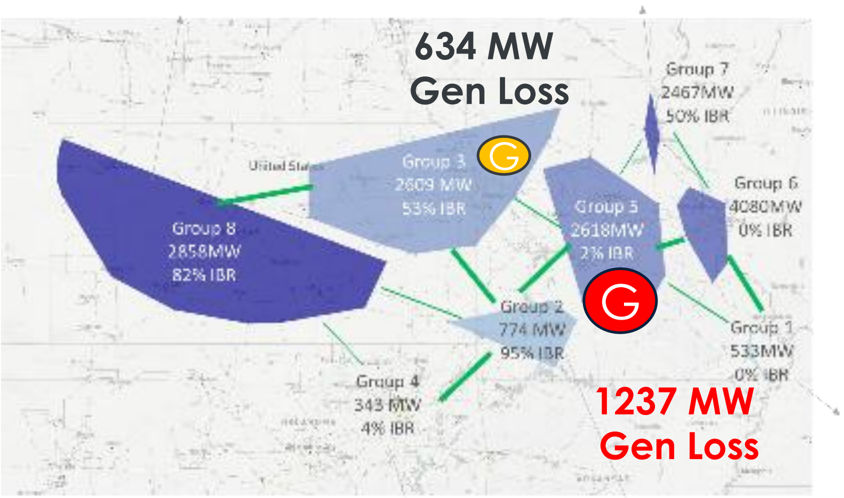
SM-Dominant Case



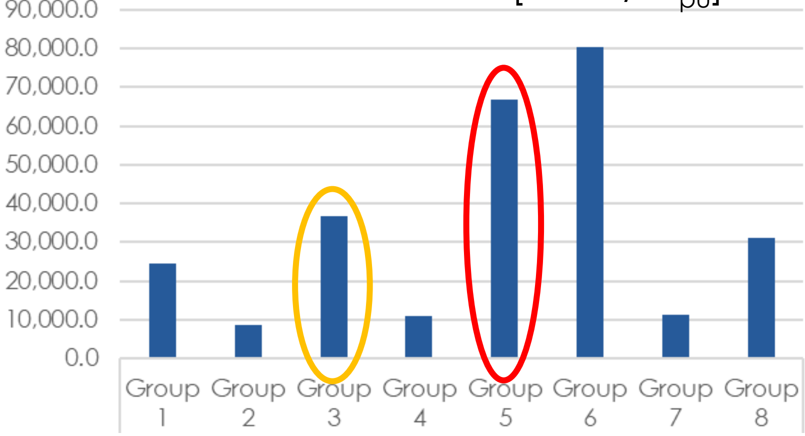
GFL Cat 1

Benchmarking: Active Power Services

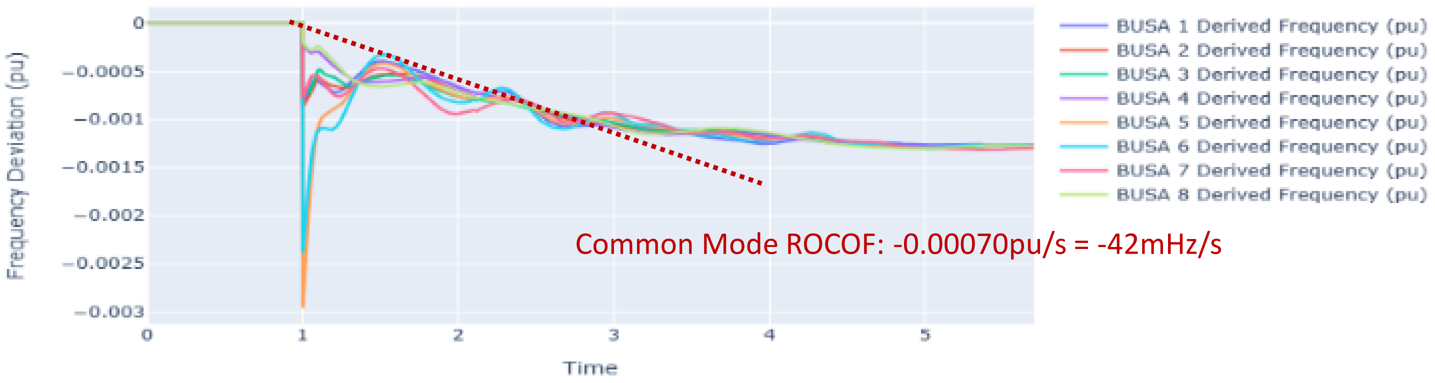
GFL (Category 1) Dominant Case



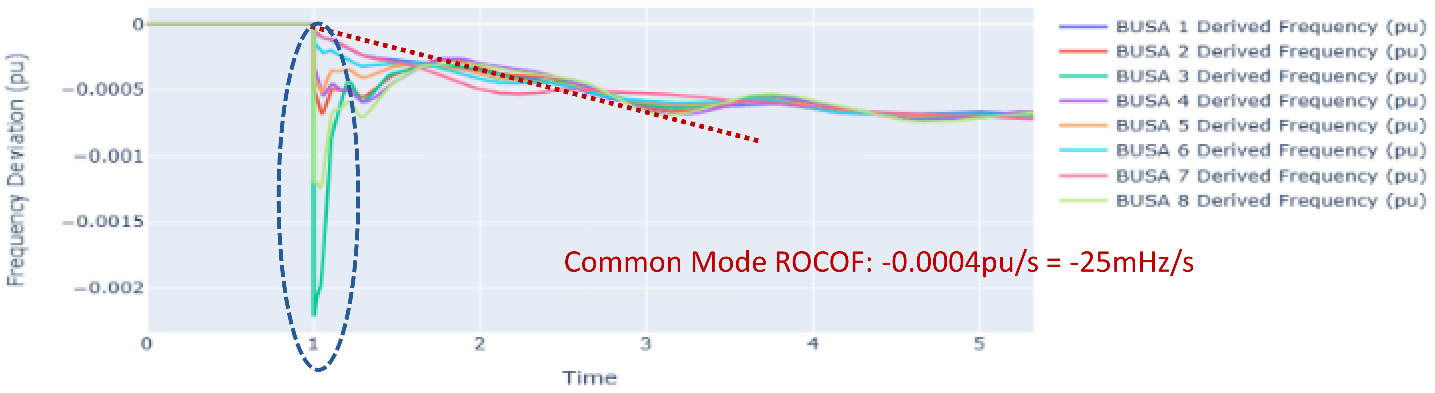
Fast Active Power [$\Delta MW/\Delta f_{pu}$]



Frequency Deviation
1237 MW Generation Loss

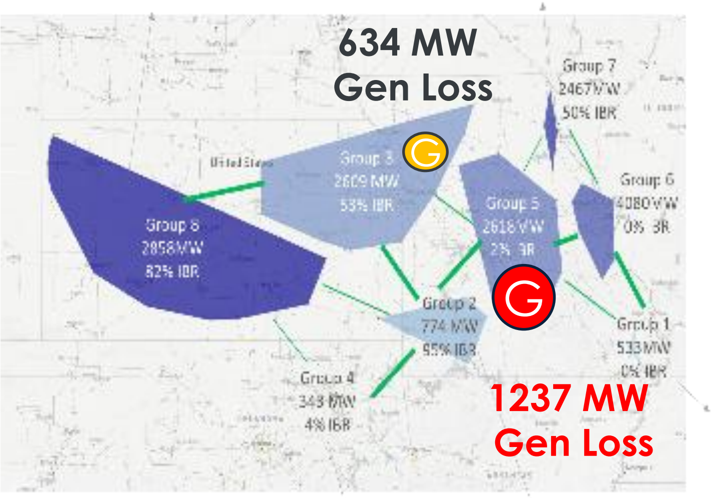


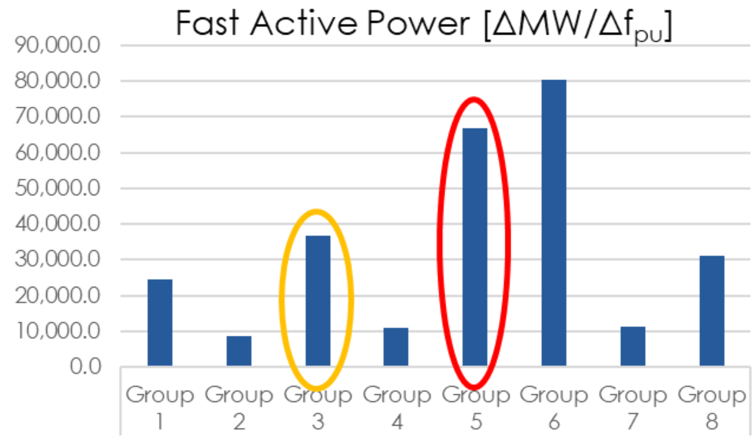
Frequency Deviation
634 MW Generation Loss



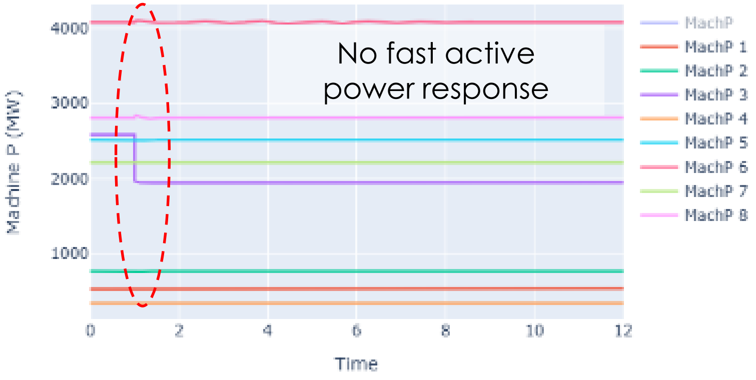
Inter-Group Support: Active Power Services

GFL (Category 1) Dominant Case

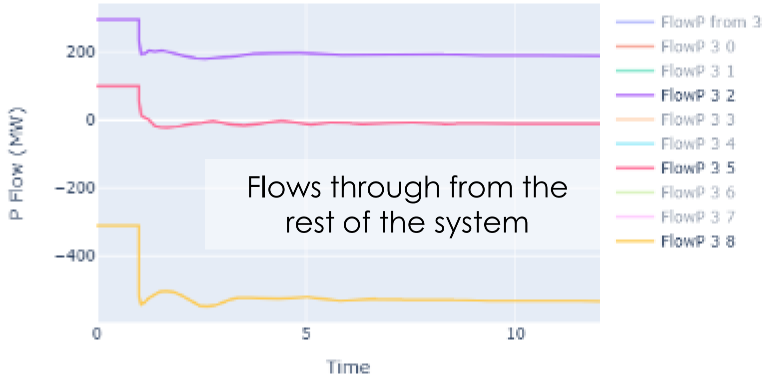




Resource Active Power, By Group
Loss of 634 MW

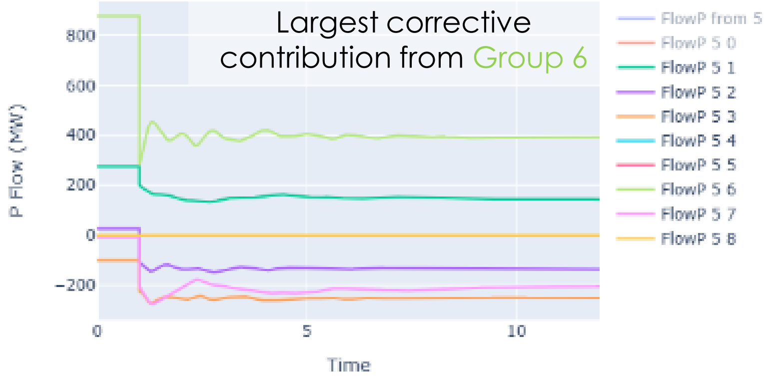


Active Power Transfer, By Group
Loss of 634 MW



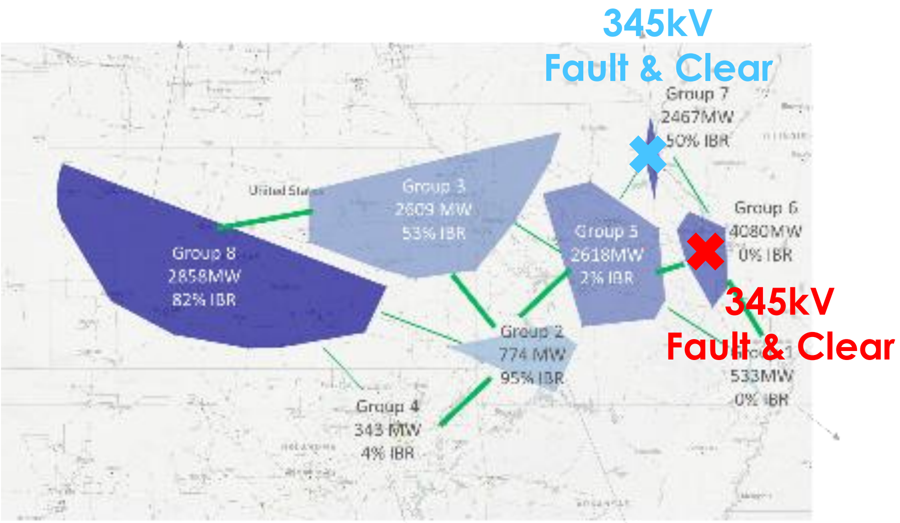
Resource Active Power, By Group
Loss of 1237 MW

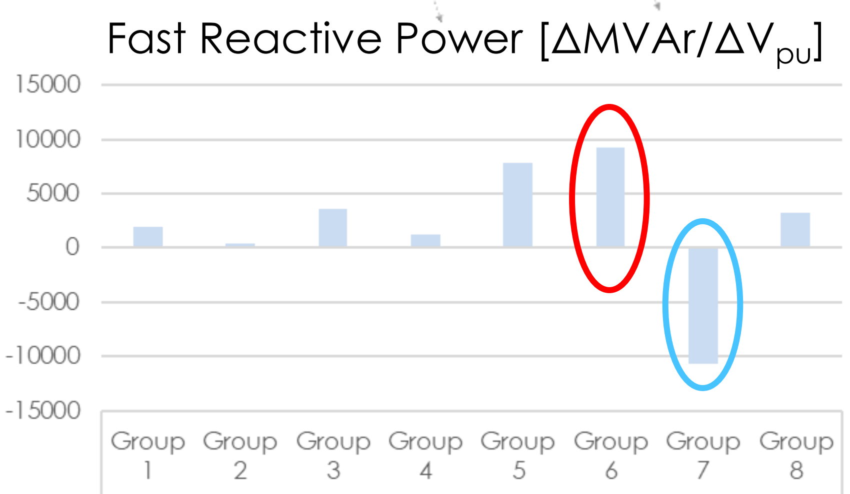
Active Power Transfer, By Group
Loss of 1237 MW



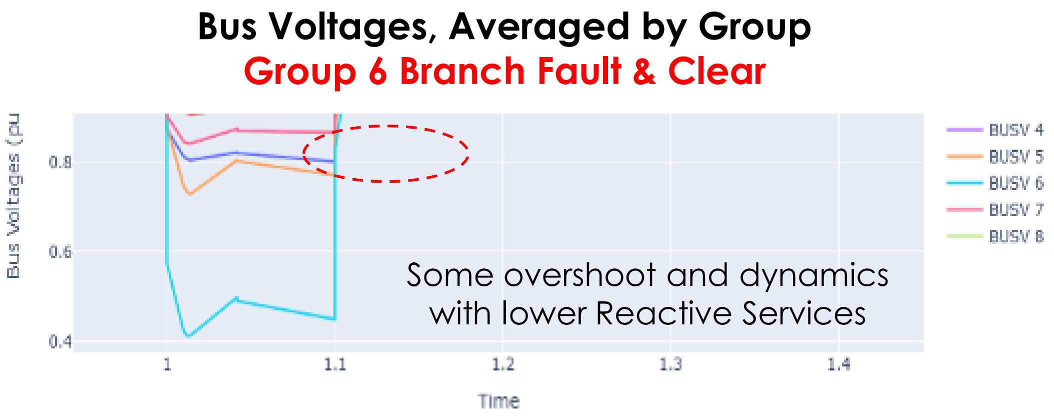
Benchmarking: Reactive Power Services

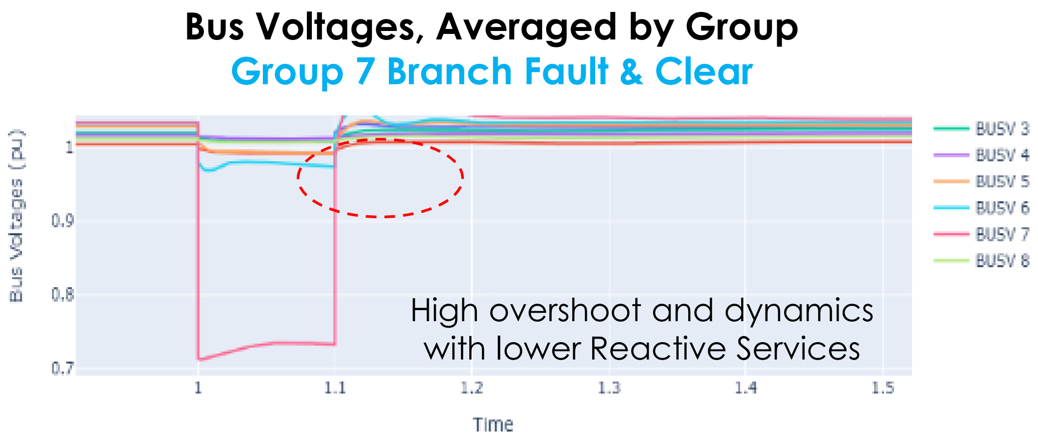
GFL (Category 1) Dominant Case





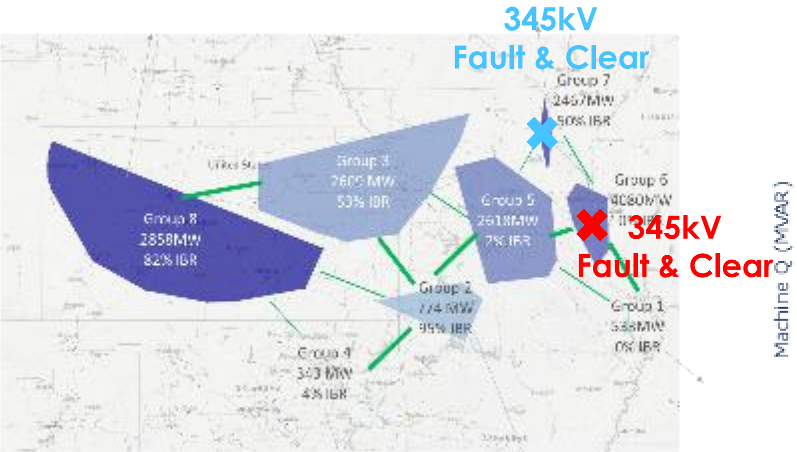
Lines were carrying 624MW (Group 6), 736 MW (Group 7)



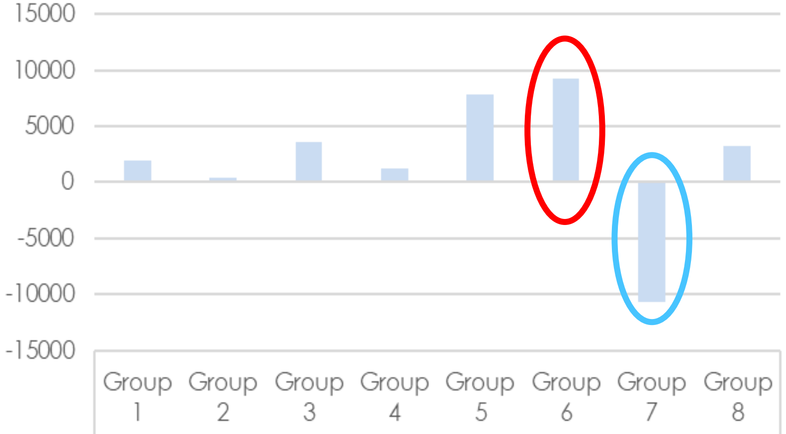


Benchmarking: Reactive Power Services

GFL (Category 1) Dominant Case

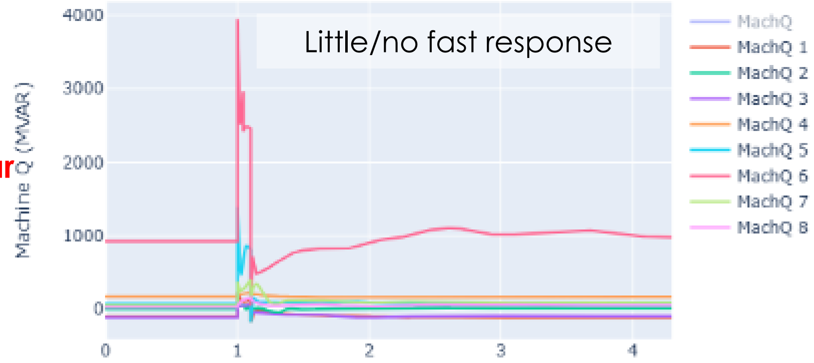


Fast Reactive Power [ΔMVAr/ΔV_{pu}]

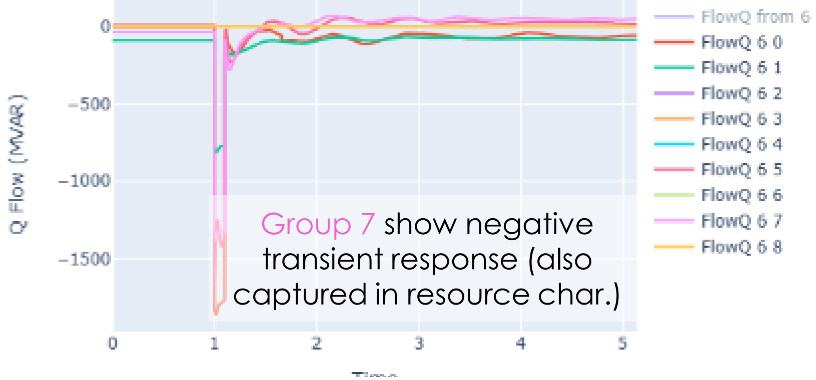


Lines were carrying 624MW (Group 6), 736 MW (Group 7)

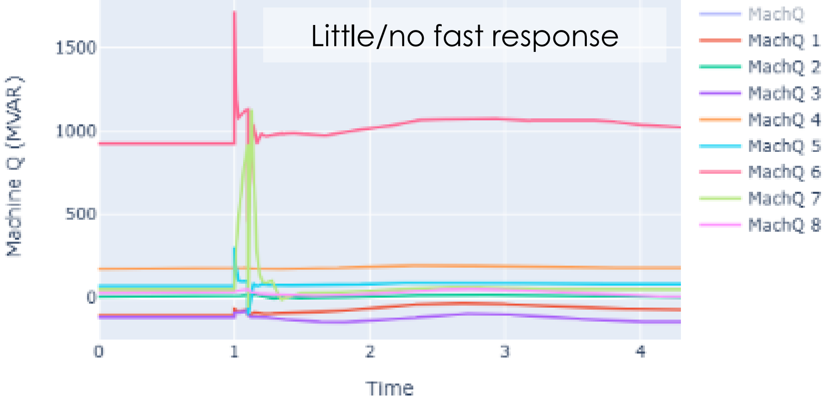
Resource Reactive Power, By Group
Group 6 Fault & Clear 345kV Line



Reactive Power Transfer, By Group
Group 6 Fault & Clear 345kV Line



Resource Reactive Power, By Group
Group 7 Fault & Clear 345kV Line



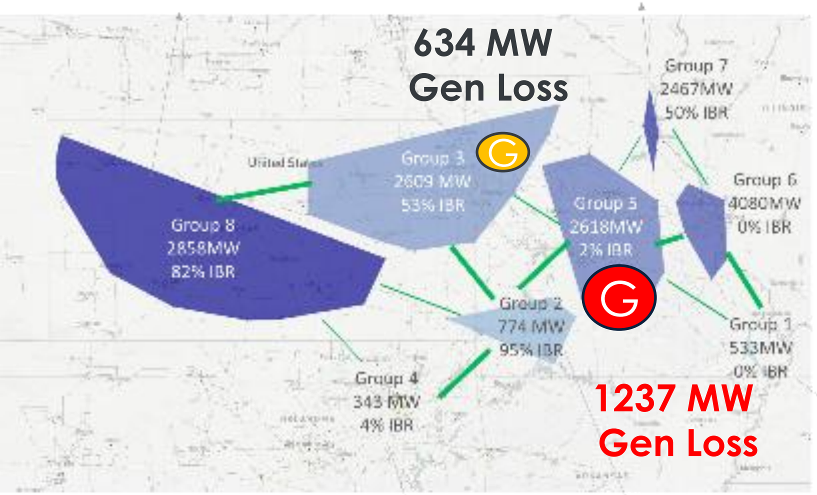
Reactive Power Transfer, By Group
Group 7 Fault & Clear 345kV Line

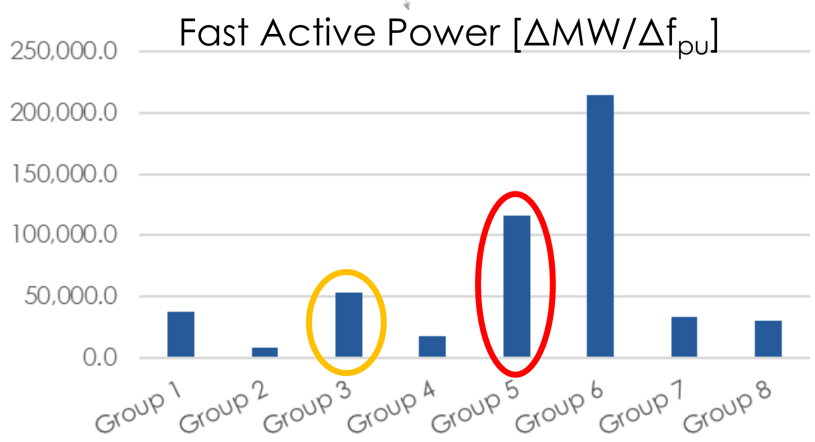
GFM-Dominant Case
(GFM Sensitivity)

ESIG
ENERGY SYSTEMS INTEGRATION GROUP

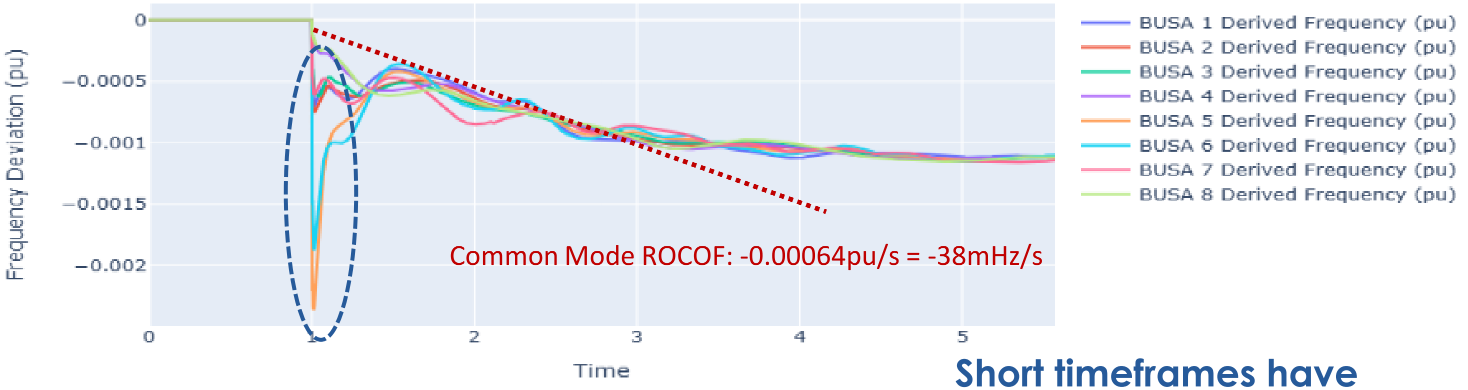
Benchmarking: Active Power Services

GFM Dominant Case



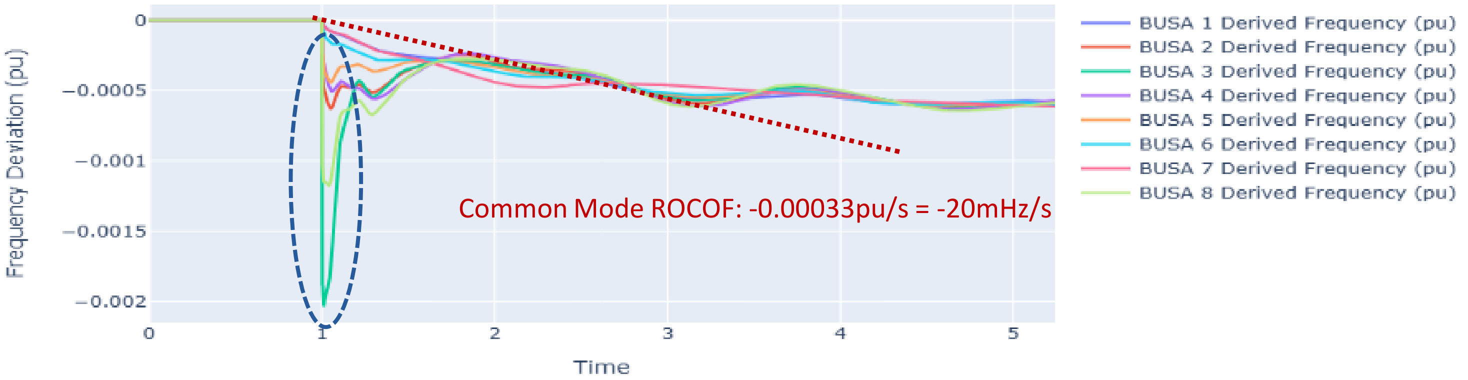


Frequency Deviation
1237 MW Generation Loss



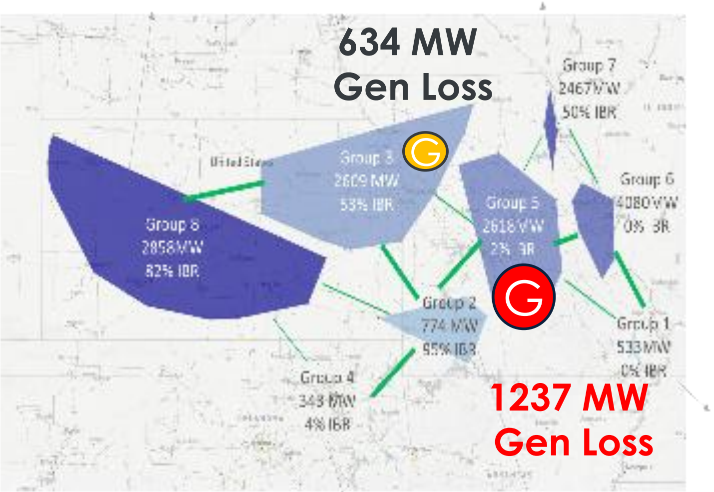
Short timeframes have significant locational differences

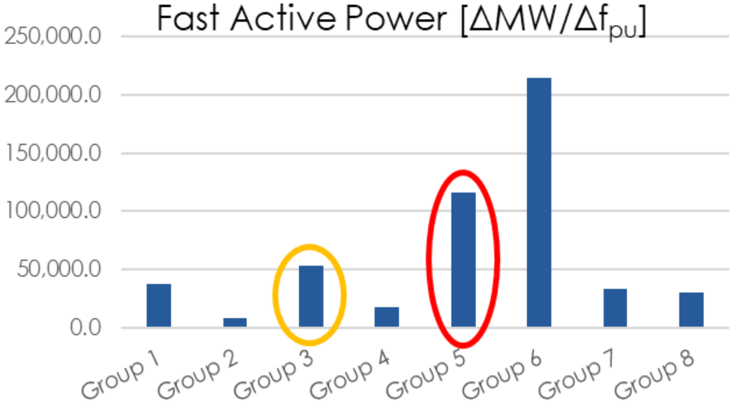
Frequency Deviation
634 MW Generation Loss



Inter-Group Support: Active Power Services

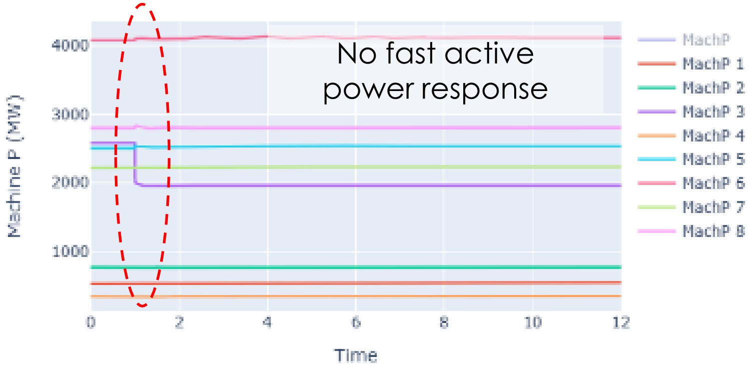
GFM Dominant Case





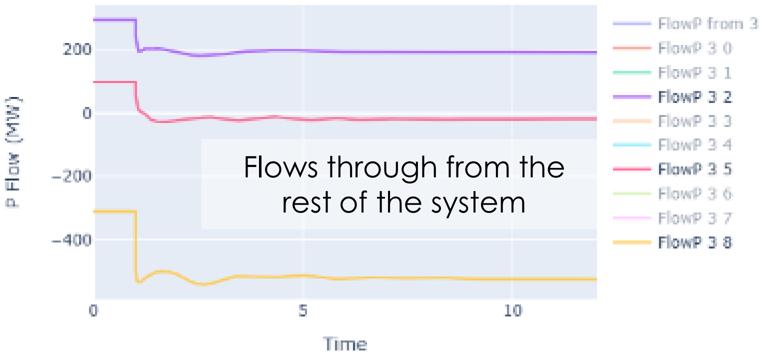
Resource Active Power, By Group

Loss of 634 MW



Active Power Transfer, By Group

Loss of 634 MW

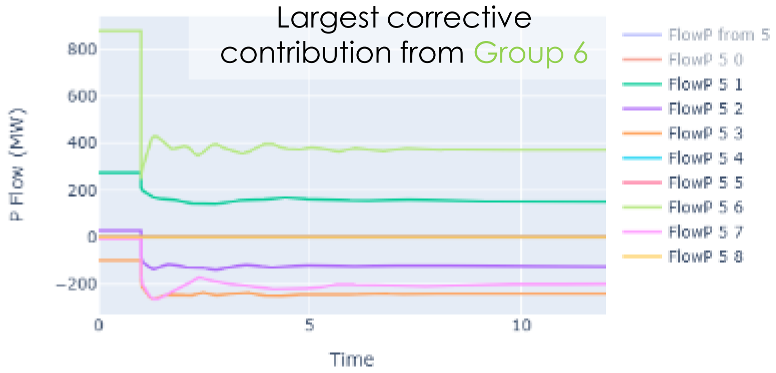


Resource Active Power, By Group

Loss of 1237 MW

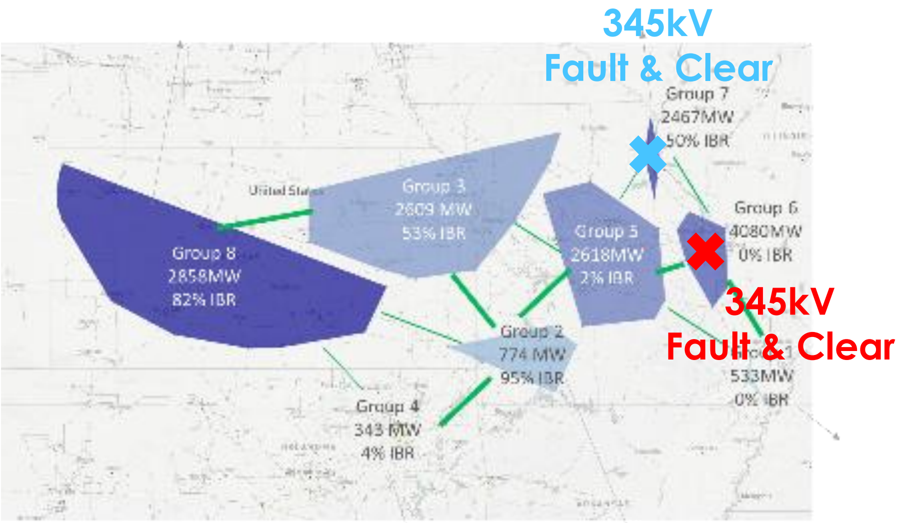
Active Power Transfer, By Group

Loss of 1237 MW

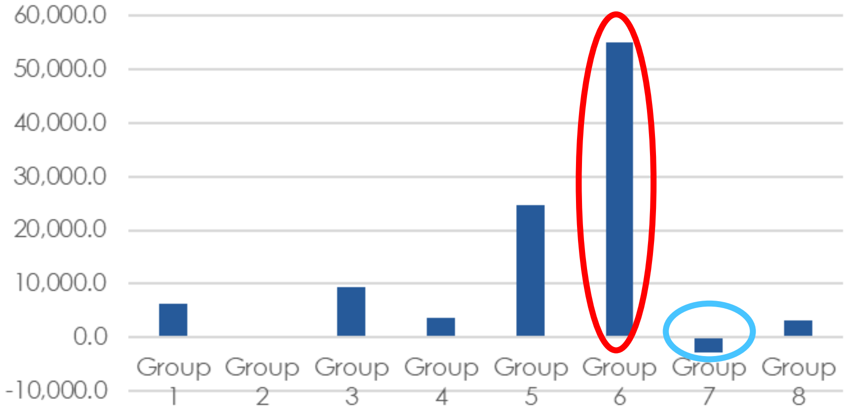


Benchmarking: Reactive Power Services

GFM Dominant Case



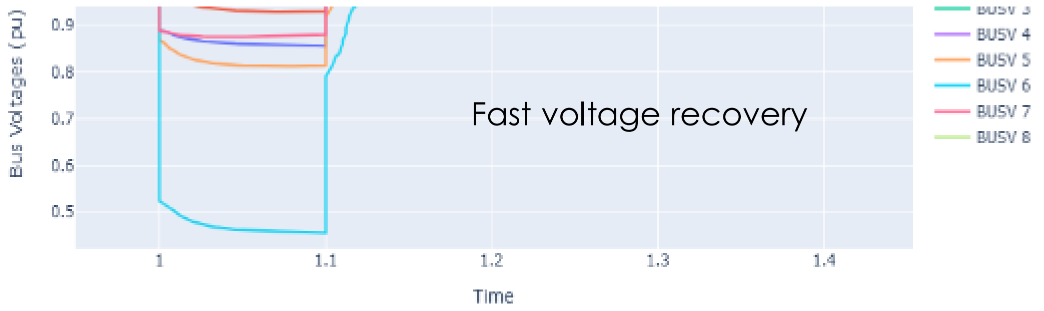
Fast Reactive Power [$\Delta MVAr/\Delta V_{pu}$]



Lines were carrying 624MW (Group 6), 736 MW (Group 7)

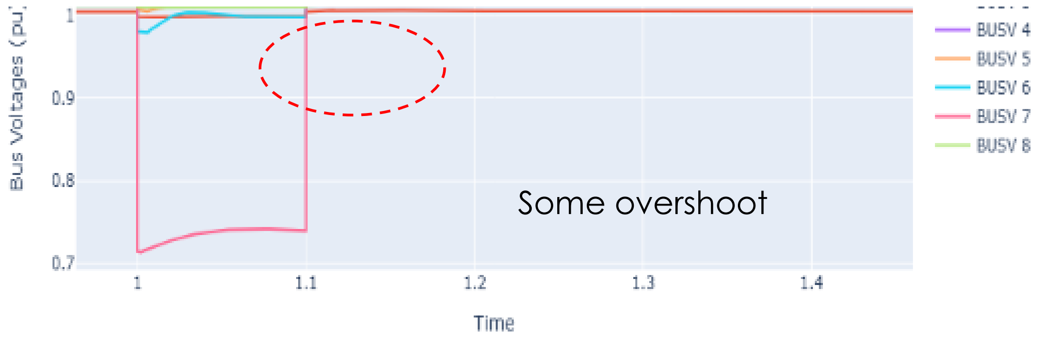
Bus Voltages, Averaged by Group

Group 6 Branch Fault & Clear



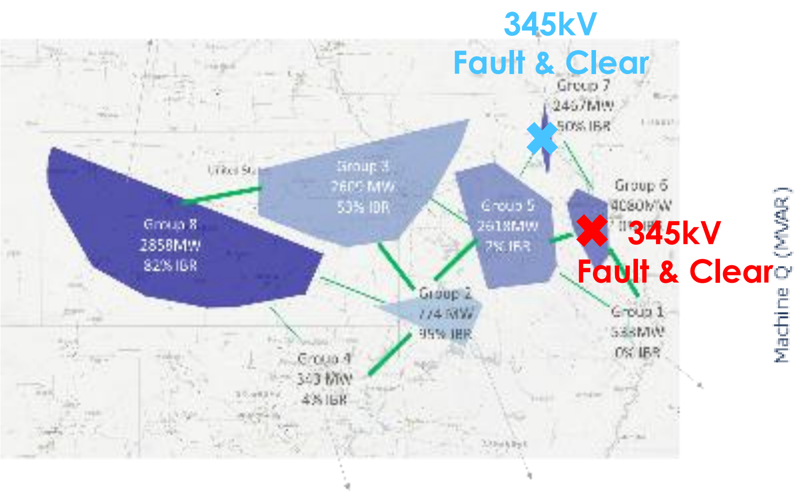
Bus Voltages, Averaged by Group

Group 7 Branch Fault & Clear

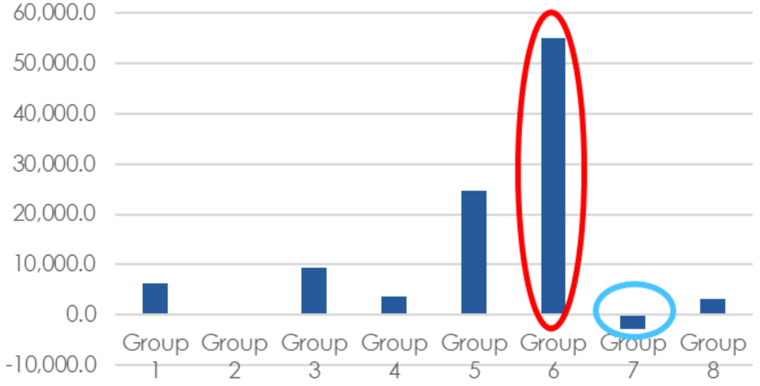


Benchmarking: Reactive Power Services

GFM Dominant Case

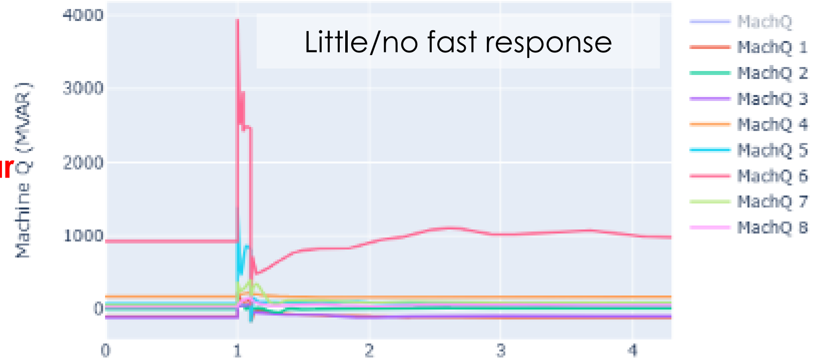


Fast Reactive Power [$\Delta MVAr/\Delta V_{pu}$]

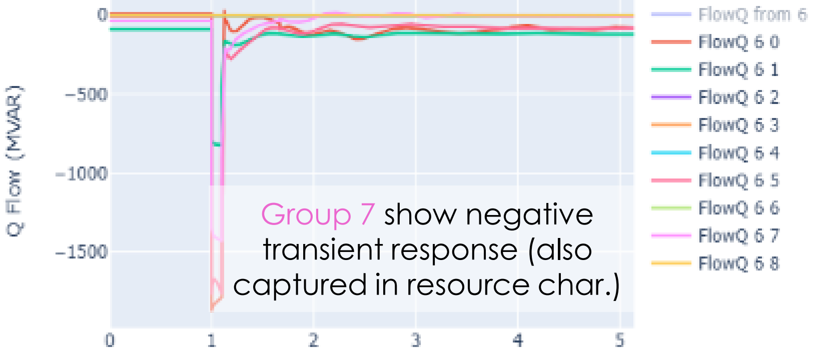


Lines were carrying 624MW (Group 6), 736 MW (Group 7)

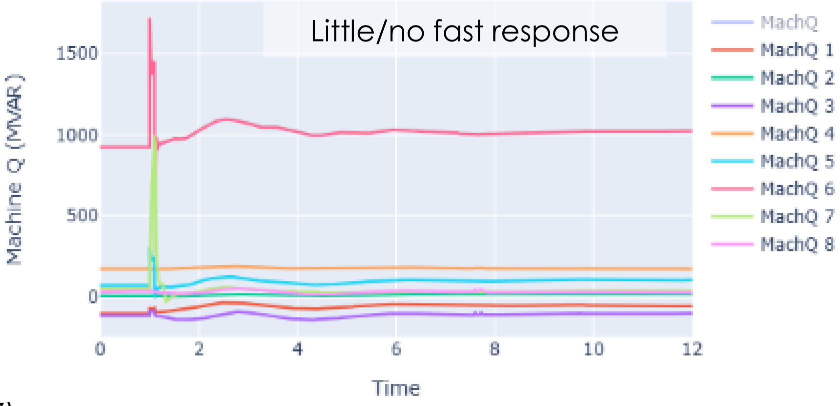
Resource Reactive Power, By Group
Group 6 Fault & Clear 345kV Line



Reactive Power Transfer, By Group
Group 6 Fault & Clear 345kV Line



Resource Reactive Power, By Group
Group 7 Fault & Clear 345kV Line

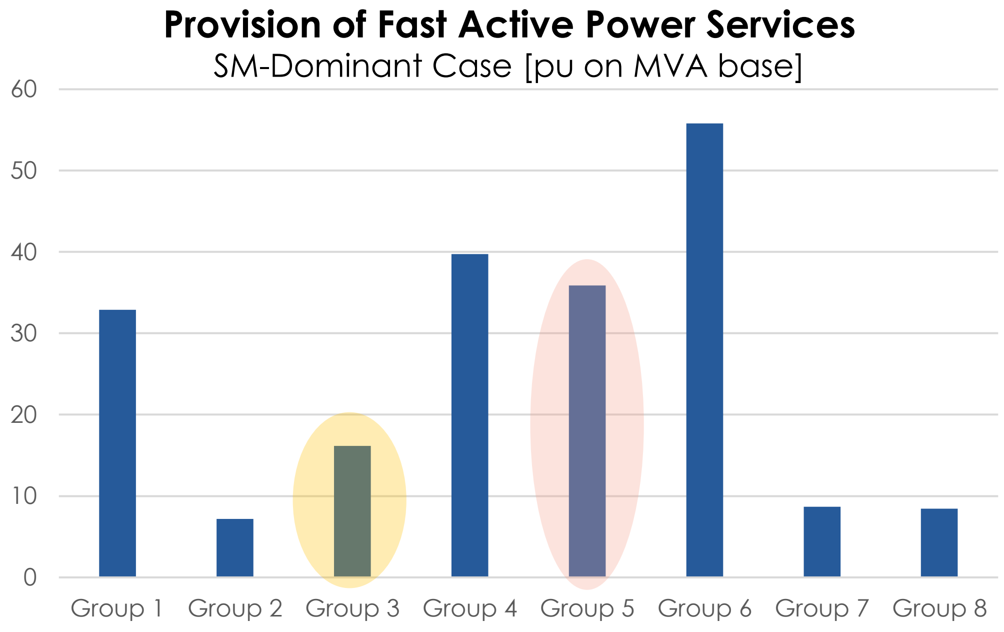


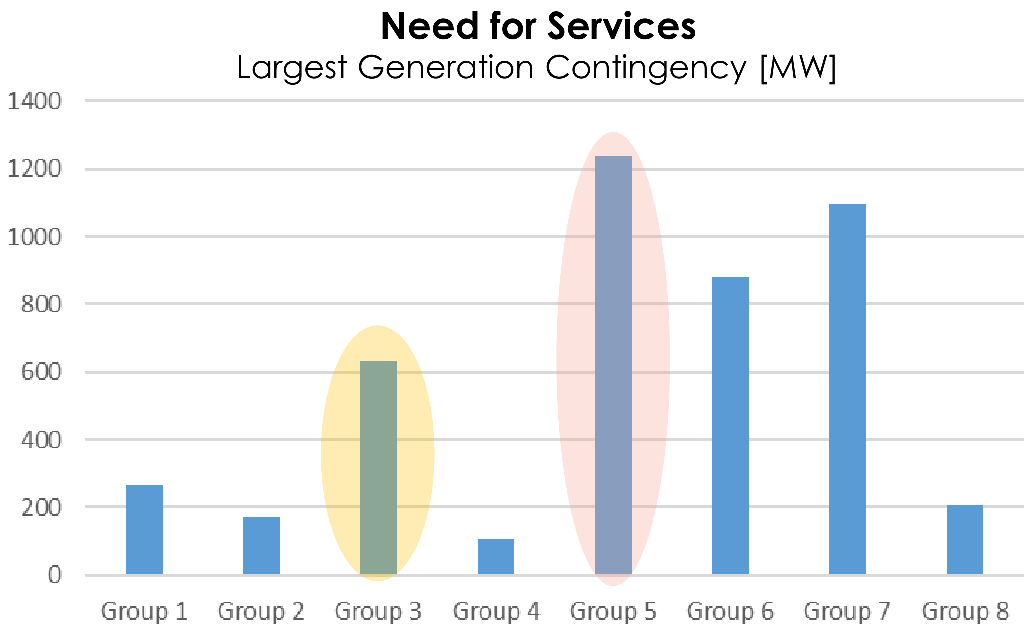
Reactive Power Transfer, By Group
Group 7 Fault & Clear 345kV Line

Comparisons

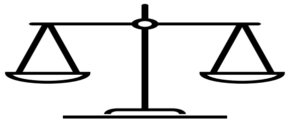
Compare: Provision & Need for Services

Consider the Fast Active Power Services, Provision & Need





- Group 3 has less fast active power services than Group 5
- But, Group 5 has a higher need for services…

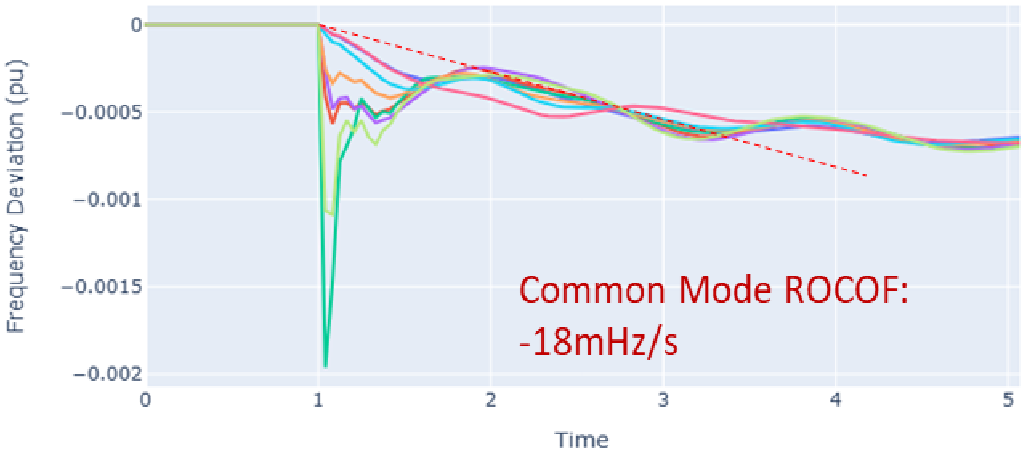


The ratio of provision / need is about the same between Group 3 and Group 5 for fast active power services!

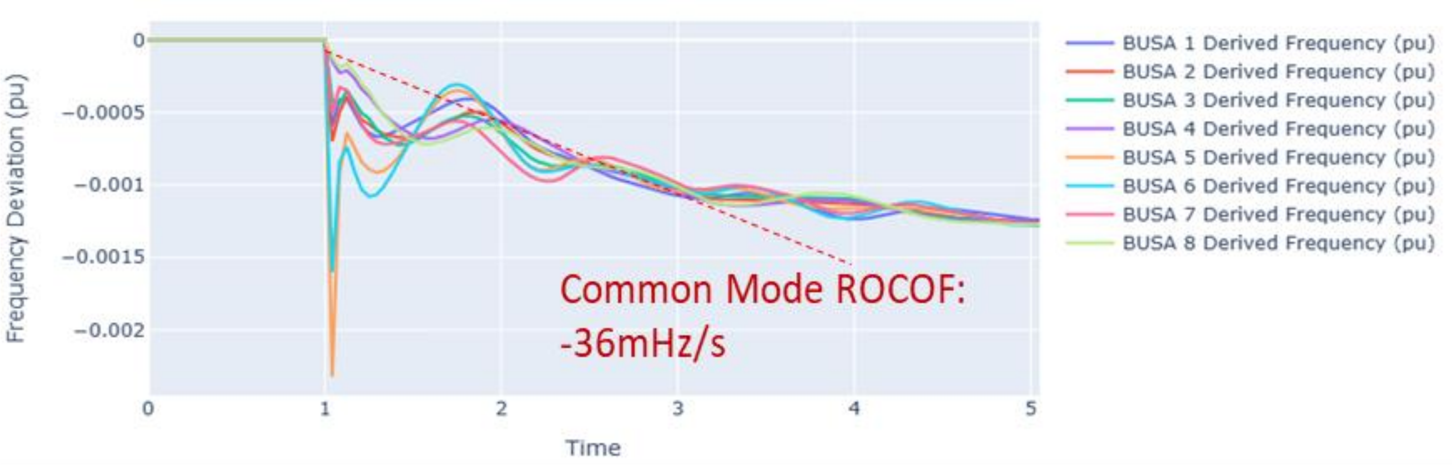
Compare: Provision & Need for Services

In the fast timeframe (< 0.1s): The local grid stress in Group 3 and Group 5 is similar (initial local frequency deviation)
In slower timeframes: Group 5 shows a larger common mode frequency deviation (larger generator outage)

Group 3 Generator Contingency
Frequency Deviation, SM-Dominant Case



Group 5 Generator Contingency
Frequency Deviation, SM-Dominant Case



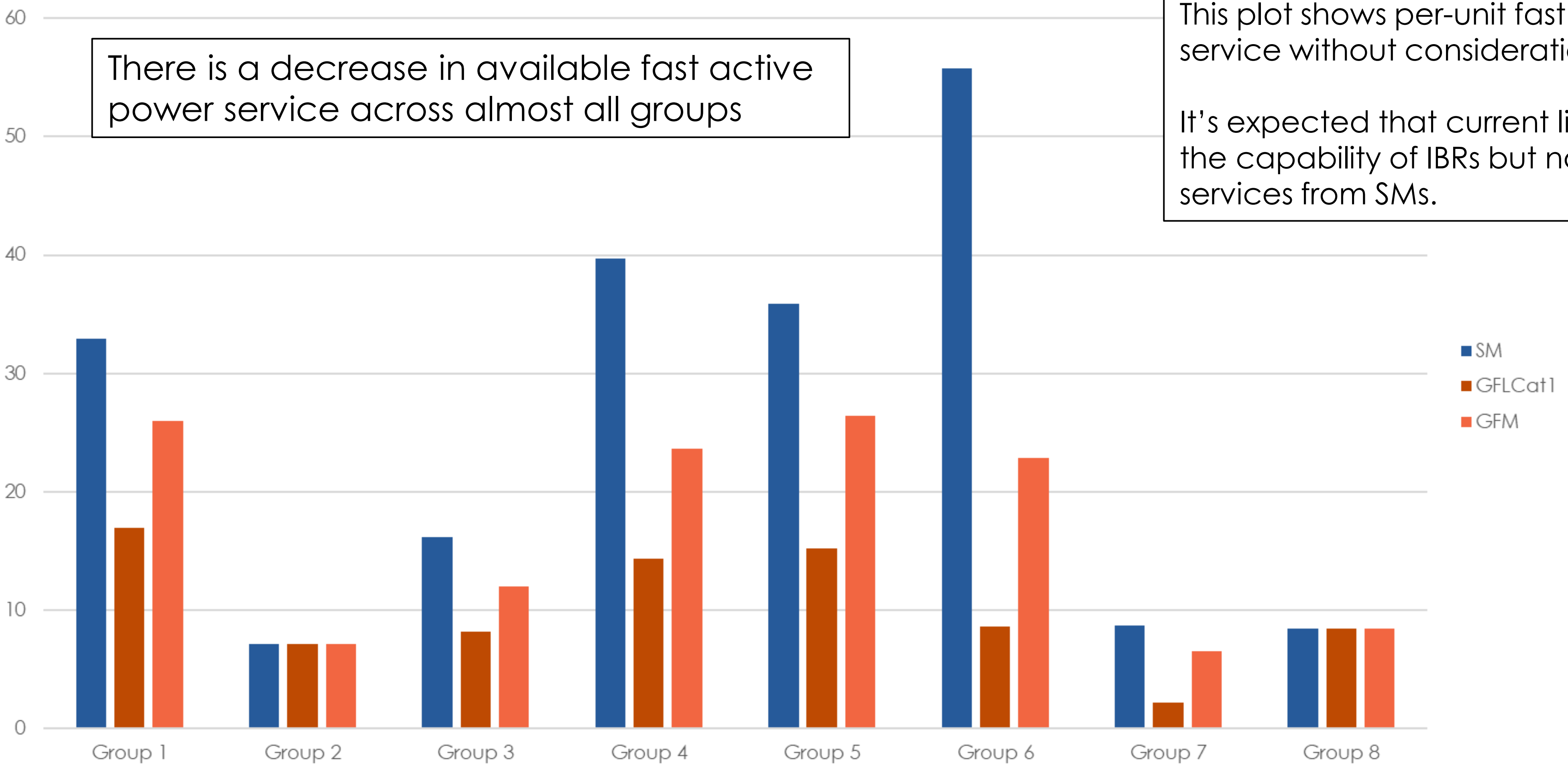
- The ratio of provision to need for services is critical
- Pockets of the grid that have few services experience more local stress
- These differences **will grow** as the grid evolves unless we keep an eye on the levels and locations of services

Comparison of Fast **Active** Power Services

There is a decrease in available fast active power service across almost all groups

This plot shows per-unit fast active power service without consideration of current limits.

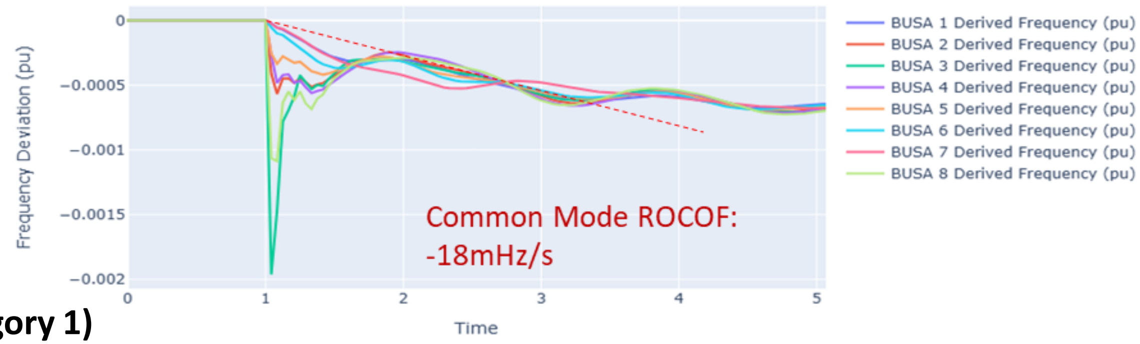
It's expected that current limits would reduce the capability of IBRs but not impact the services from SMs.



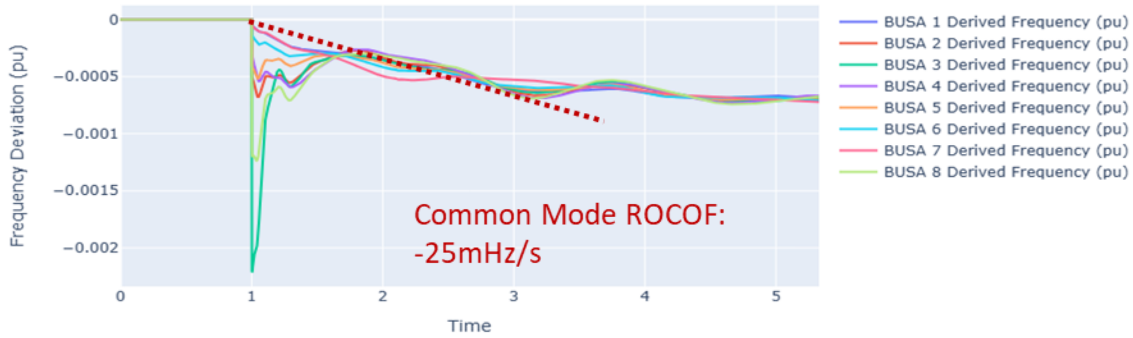
All plots in per-unit on group online MVA base

Benchmarking Fast **Active** Power Services
Loss of Generator Contingency, Group 3

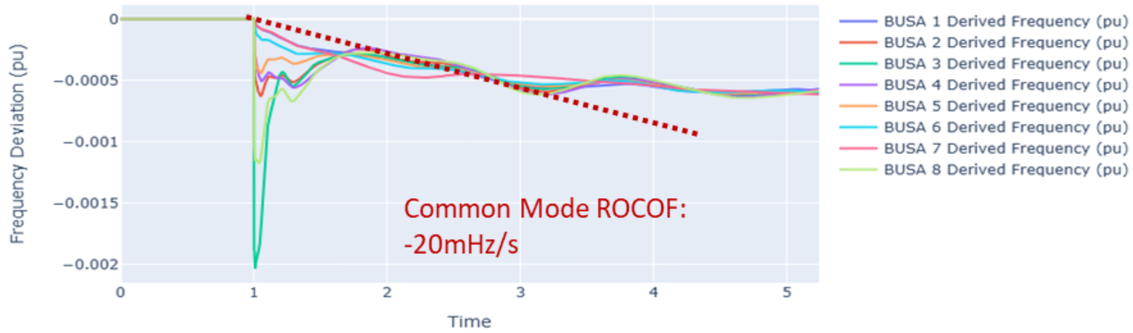
SM-Dominant Case



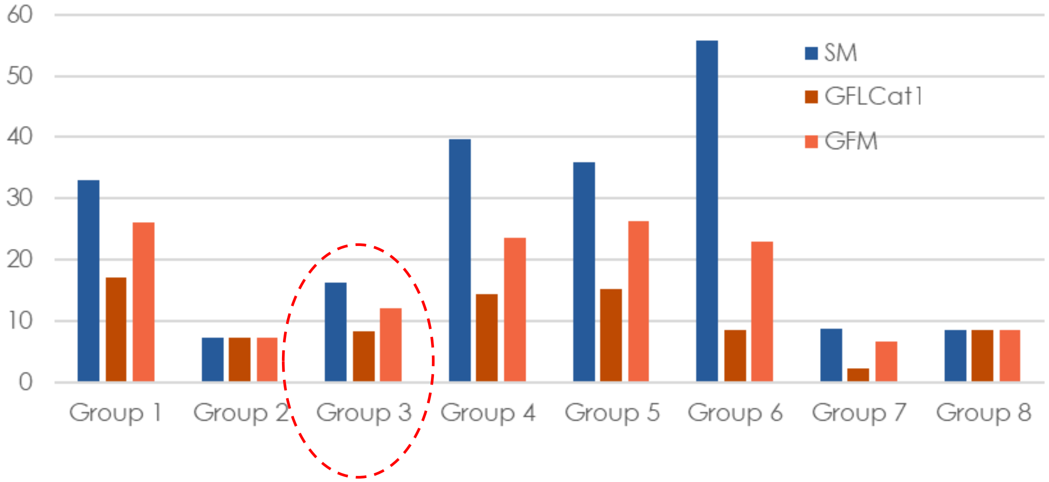
GFL (Category 1)



GFM



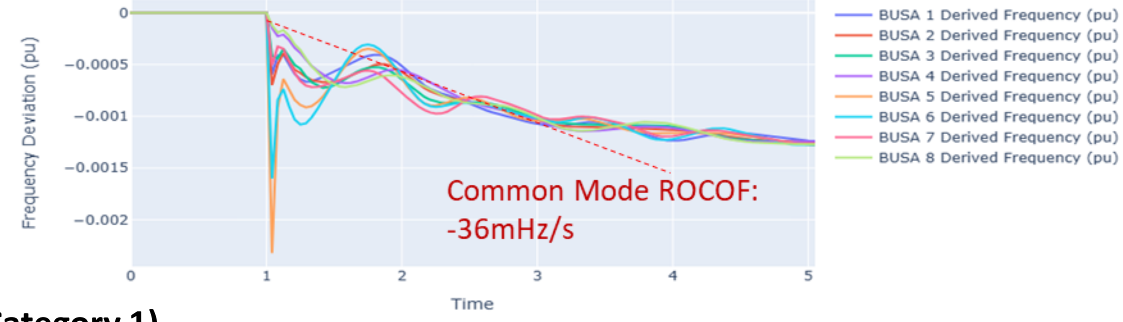
Loss 634 MW generator in Group 3



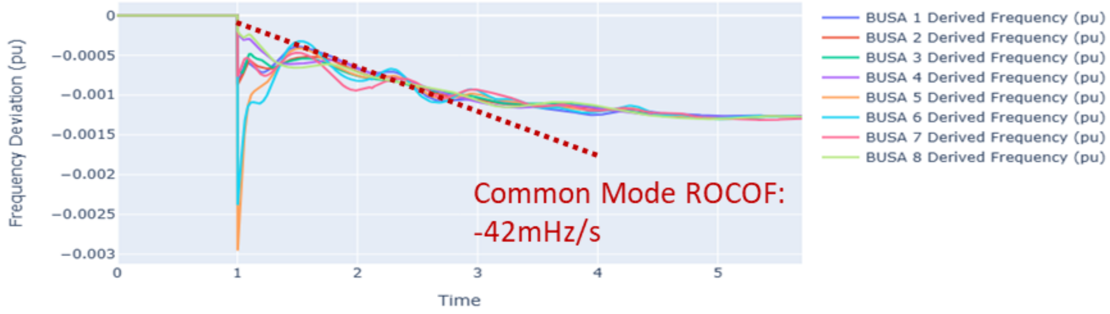
The trends from the time domain results correspond with the framework

Benchmarking Fast **Active** Power Services
Loss of Generator Contingency, Group 5

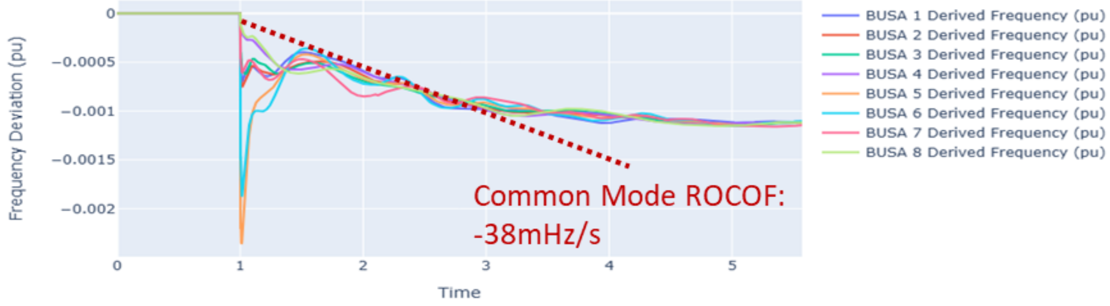
SM-Dominant Case



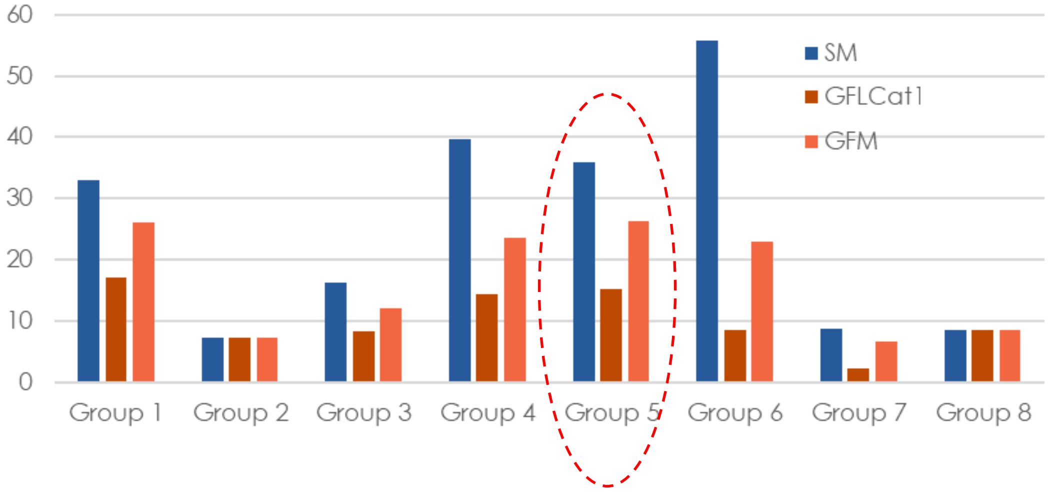
GFL (Category 1)



GFM



Loss of 1237 MW generator in Group 5



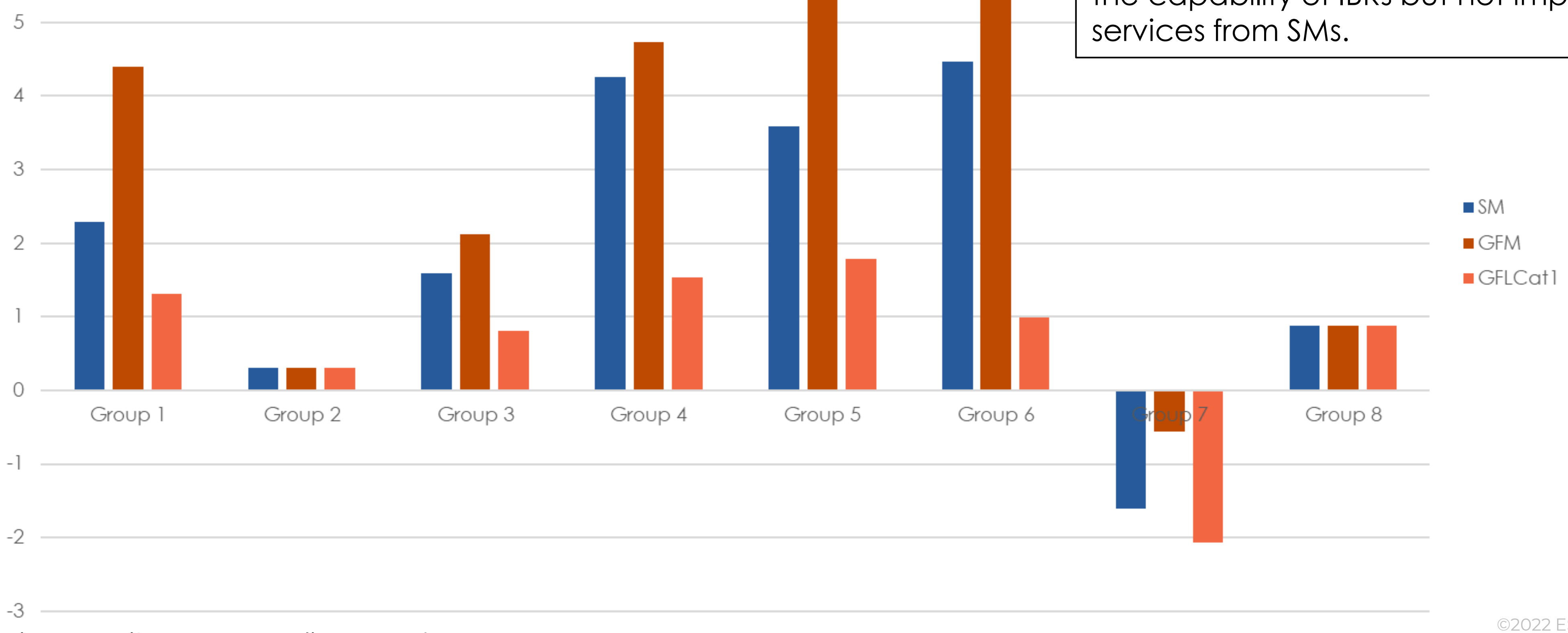
The trends from the time domain results correspond with the framework

Change in Fast Reactive Power Services

The GFL case consistently has reduced fast reactive power service, while the GFM has increased fast reactive power service.

This plot shows per-unit fast reactive power service without consideration of current limits.

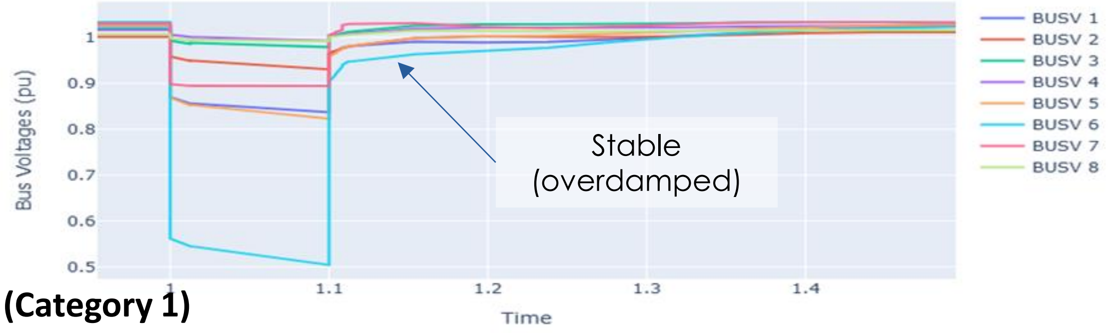
It's expected that current limits would reduce the capability of IBRs but not impact the services from SMs.



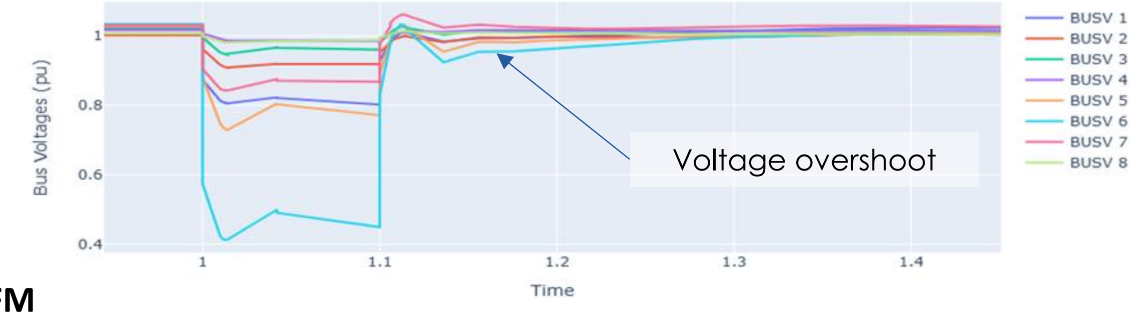
All plots in per-unit on group online MVA base

Benchmarking Fast **Reactive** Power Services
Branch Fault & Clear Contingency in Group 6

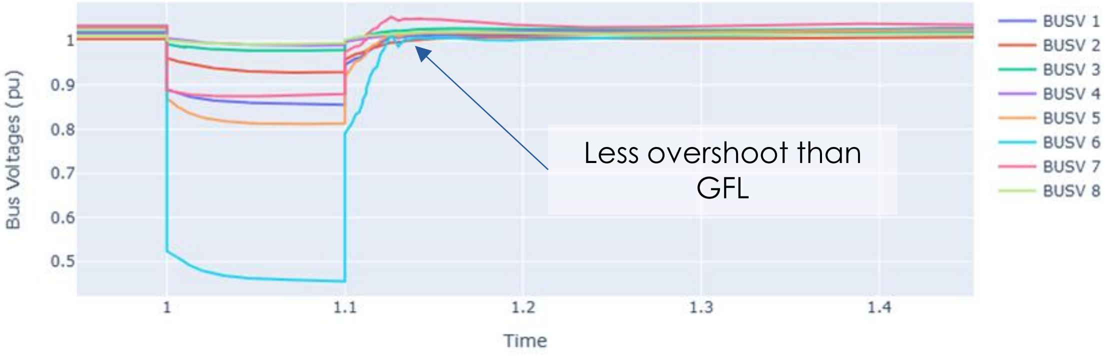
SM-Dominant Case

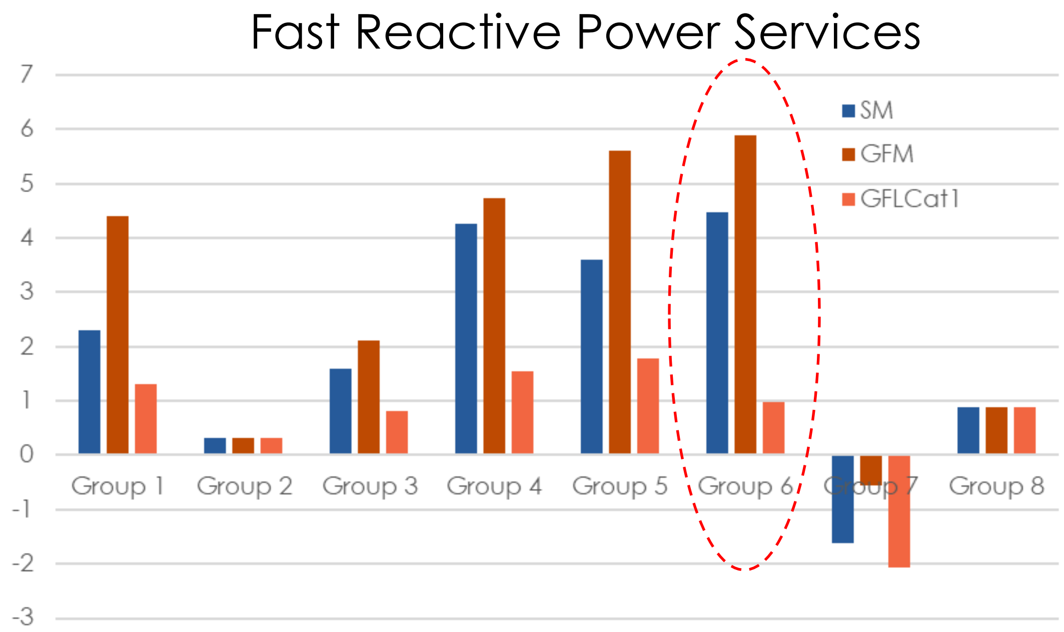


GFL (Category 1)



GFM

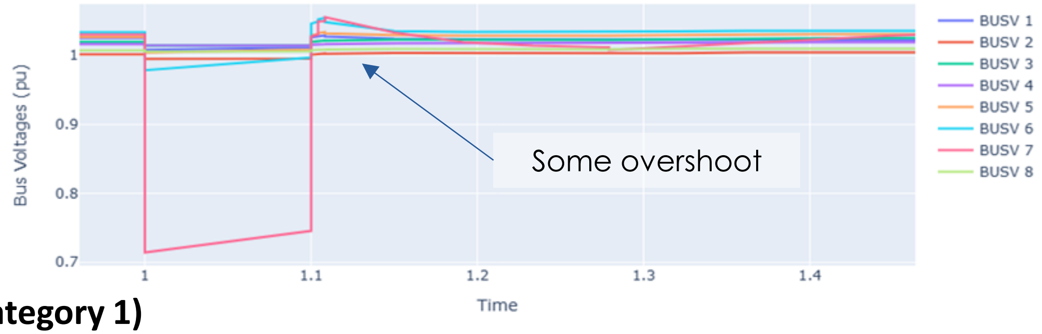




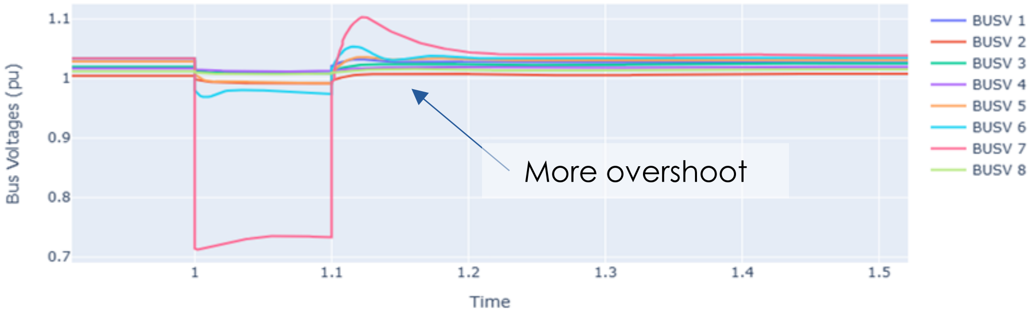
The trends from the time domain results correspond with the framework

Benchmarking Fast **Reactive** Power Services
Branch Fault & Clear Contingency in Group 7

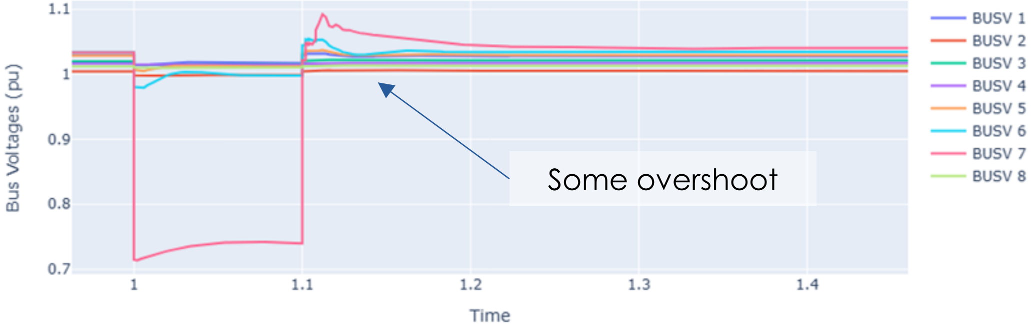
SM-Dominant Case

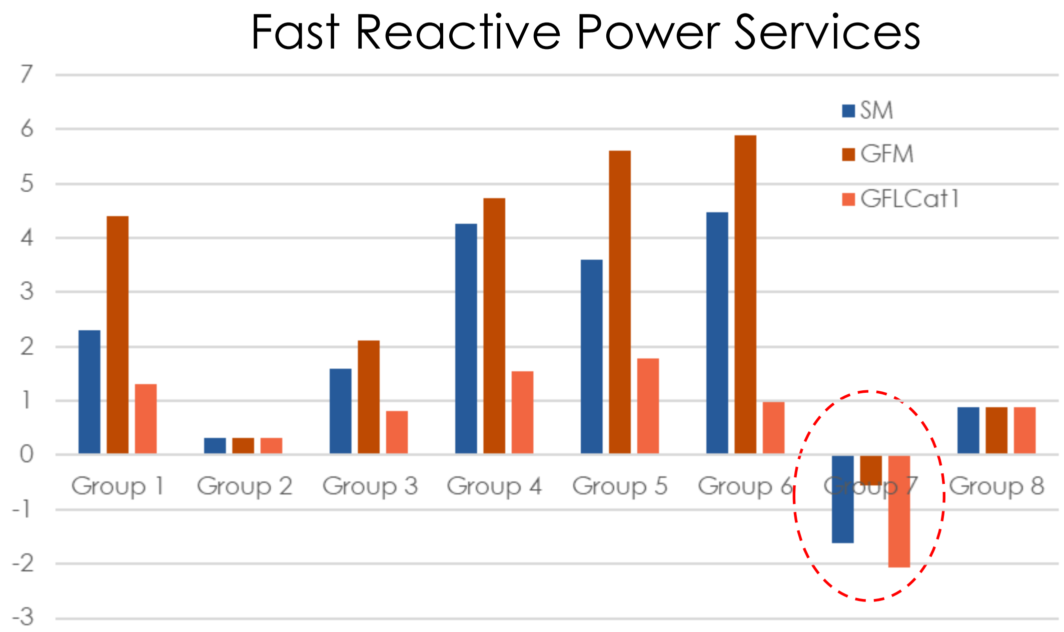


GFL (Category 1)



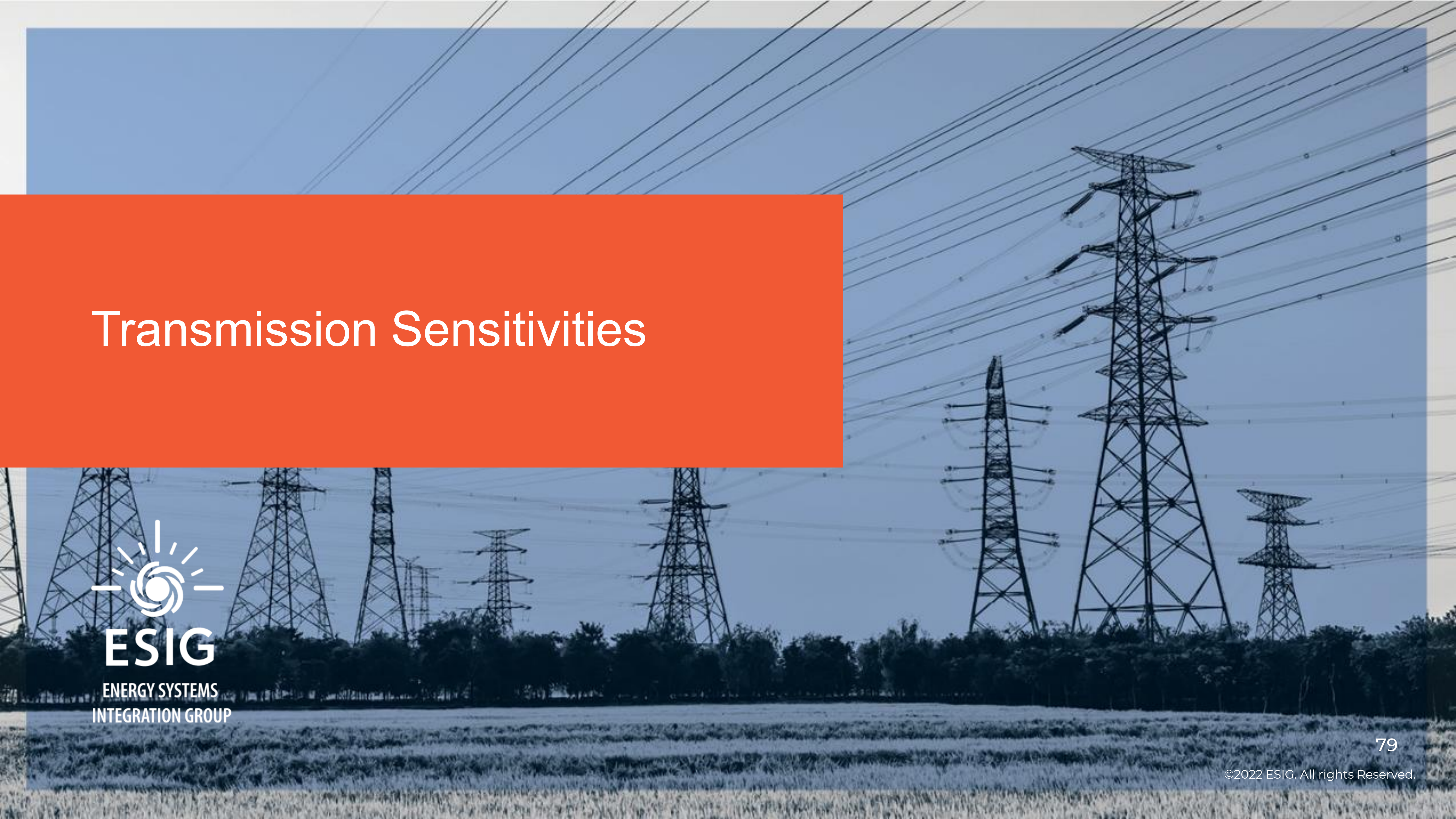
GFM





The trends (resource provision & location) from the time domain results correspond with the framework

Transmission Sensitivities

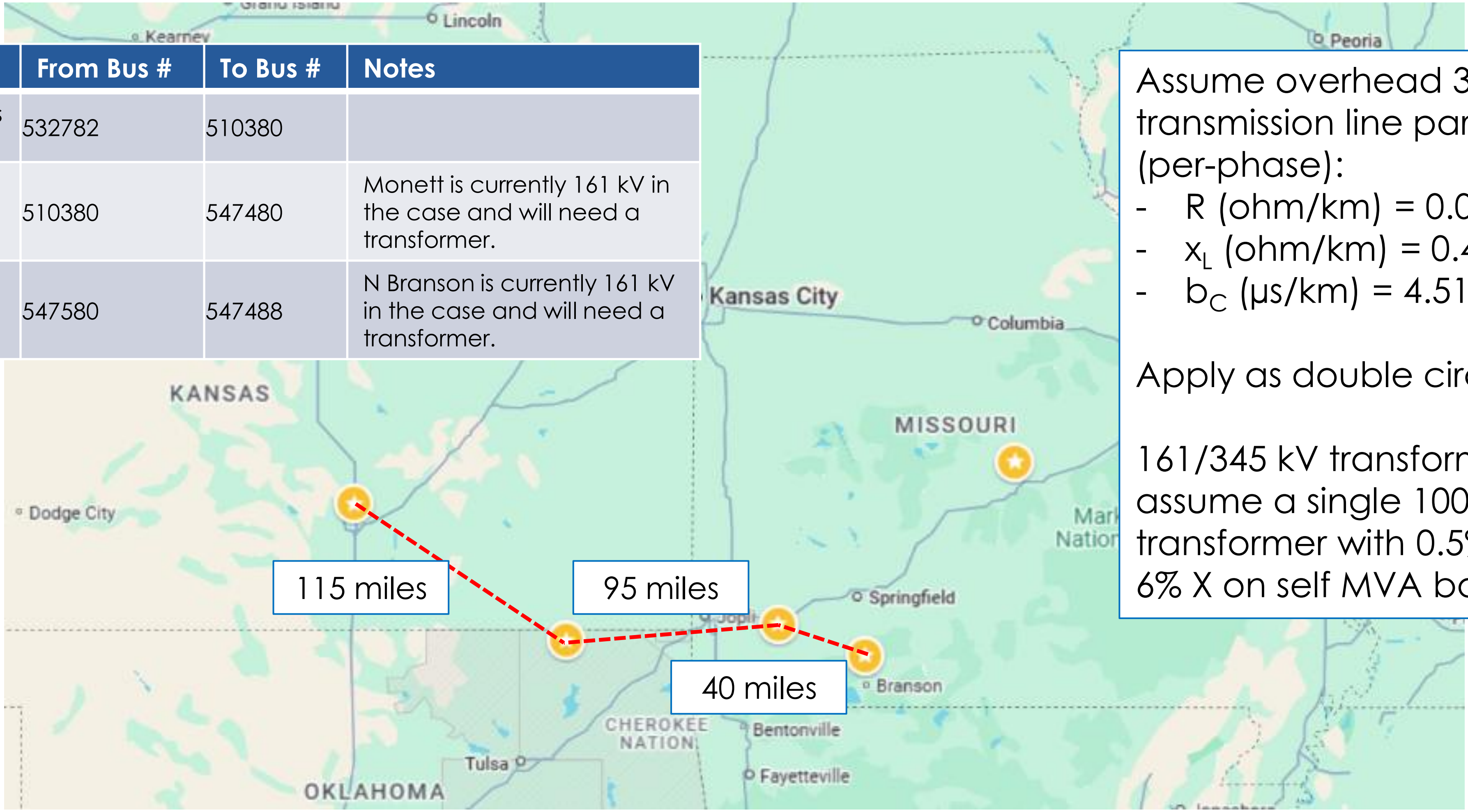


Transmission Sensitivity # 1

From SPP 2024 ITP

Buffalo Flats – Delaware – Monett – N Branson 345 kV New Line

Line	From Bus #	To Bus #	Notes
Buffalo Flats - Delaware	532782	510380	
Delaware - Monett	510380	547480	Monett is currently 161 kV in the case and will need a transformer.
Monett – N Branson	547580	547488	N Branson is currently 161 kV in the case and will need a transformer.



Assume overhead 345 kV transmission line parameters (per-phase):

- R (ohm/km) = 0.037
- x_L (ohm/km) = 0.488
- b_C (μs/km) = 4.518

Apply as double circuit

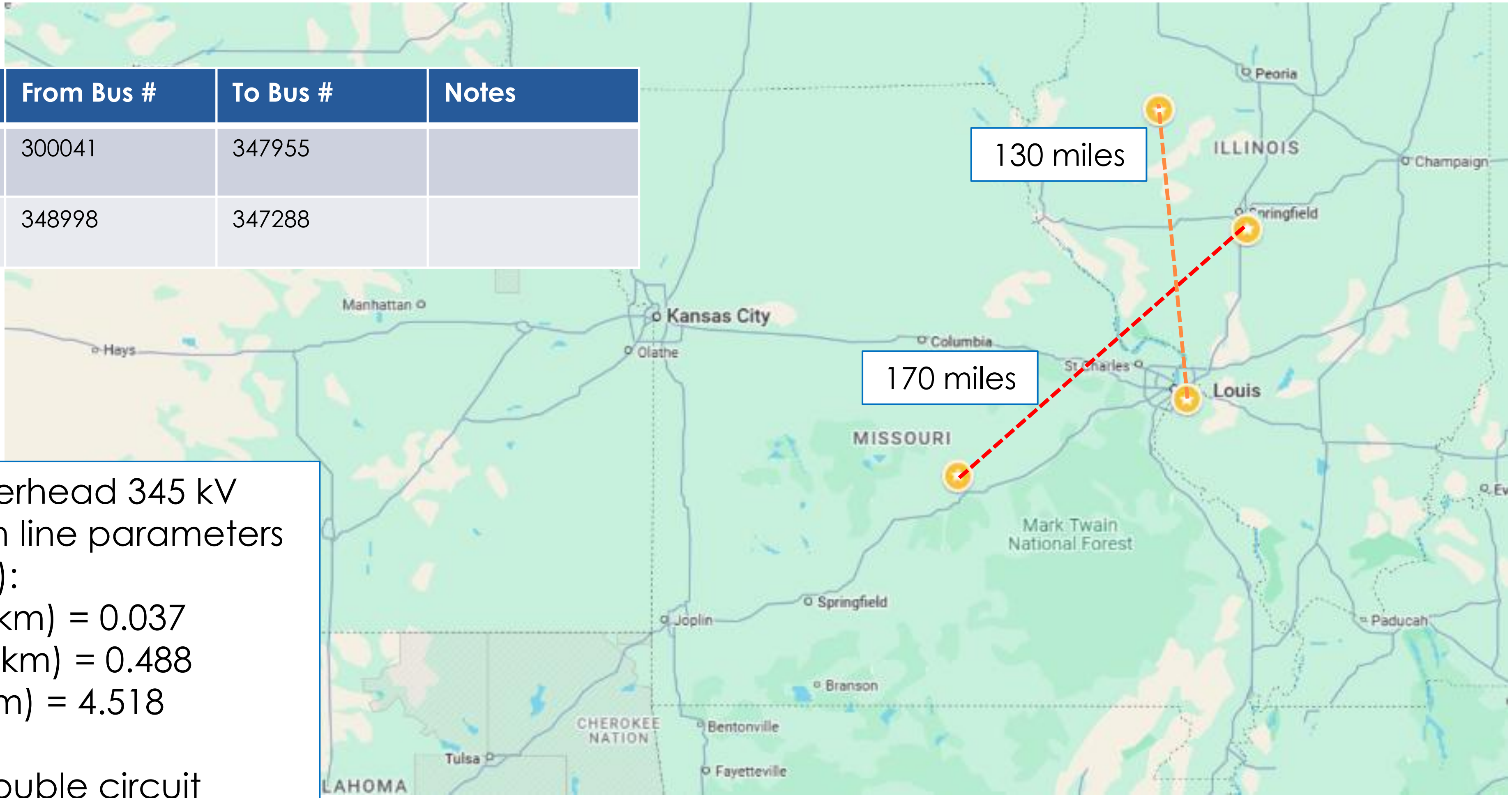
161/345 kV transformer – assume a single 1000 MVA transformer with 0.5% R and 6% X on self MVA base

Transmission Sensitivity #2

Hypothetical Example Projects

Franks – Austin & Beehive – Ipava New 345 kV Lines

Line	From Bus #	To Bus #	Notes
Franks – Austin 345 kV	300041	347955	
Beehive – Ipava 345 kV	348998	347288	

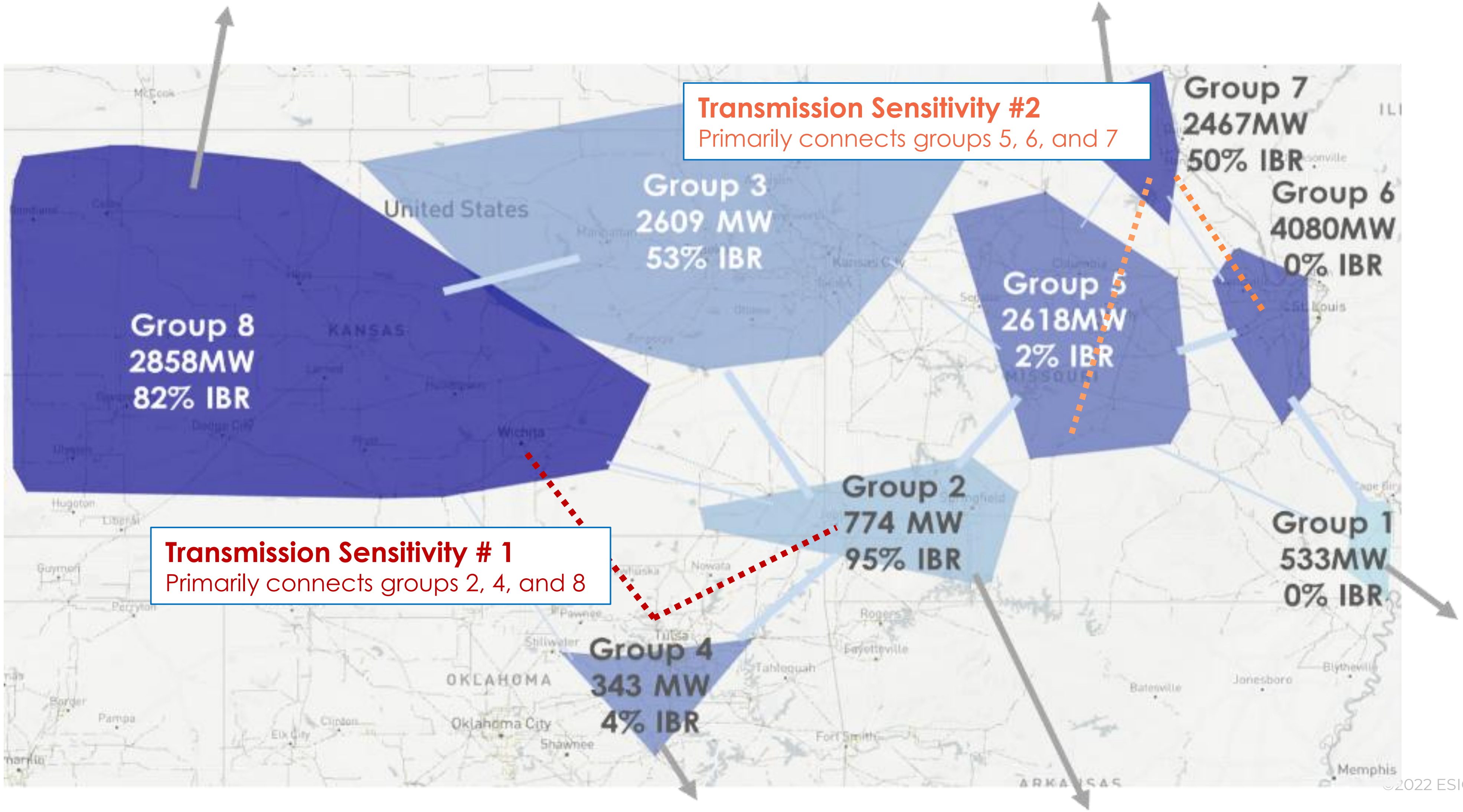


Assume overhead 345 kV transmission line parameters (per-phase):

- R (ohm/km) = 0.037
- x_L (ohm/km) = 0.488
- b_C (μs/km) = 4.518

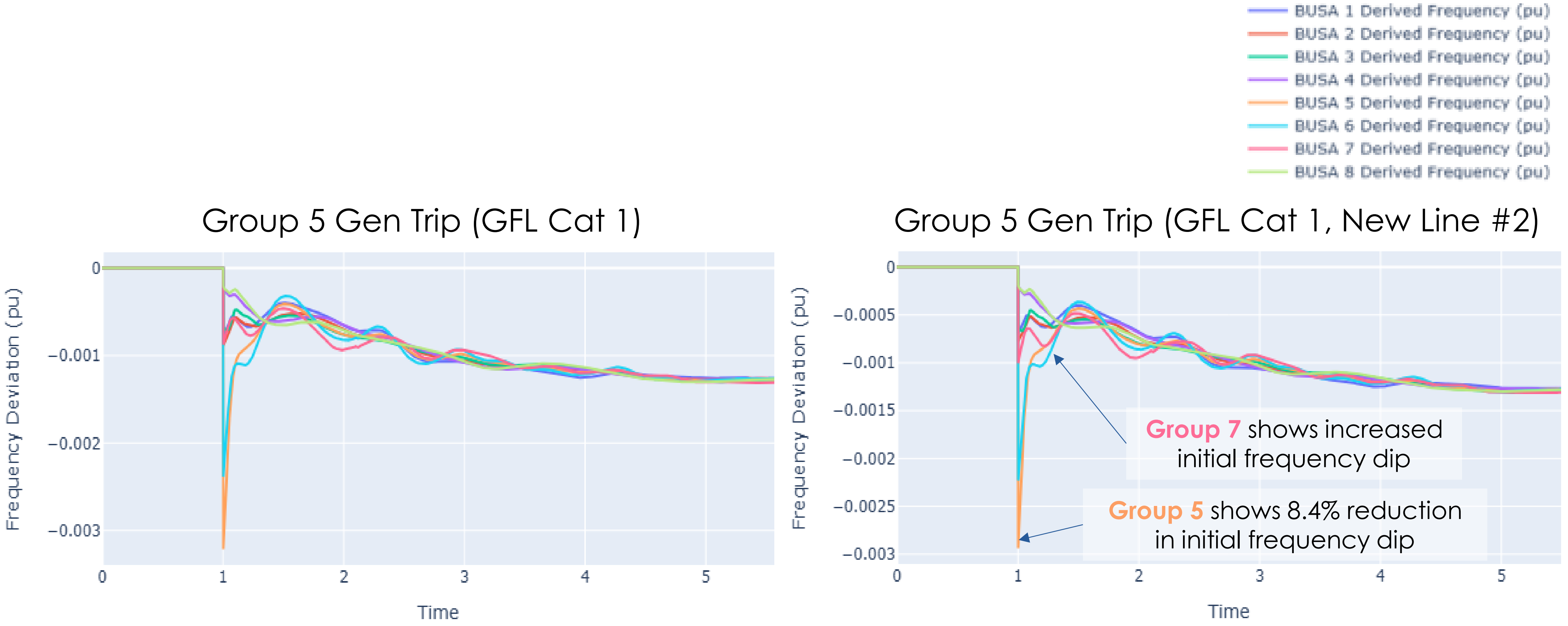
Apply as double circuit

Transmission Sensitivities by Group



Transmission – Gen Trip Comparison

GFL (Category 1) Dominant Case
Loss of 1237 MW Generator in Group 5 - Transmission Sensitivity #2

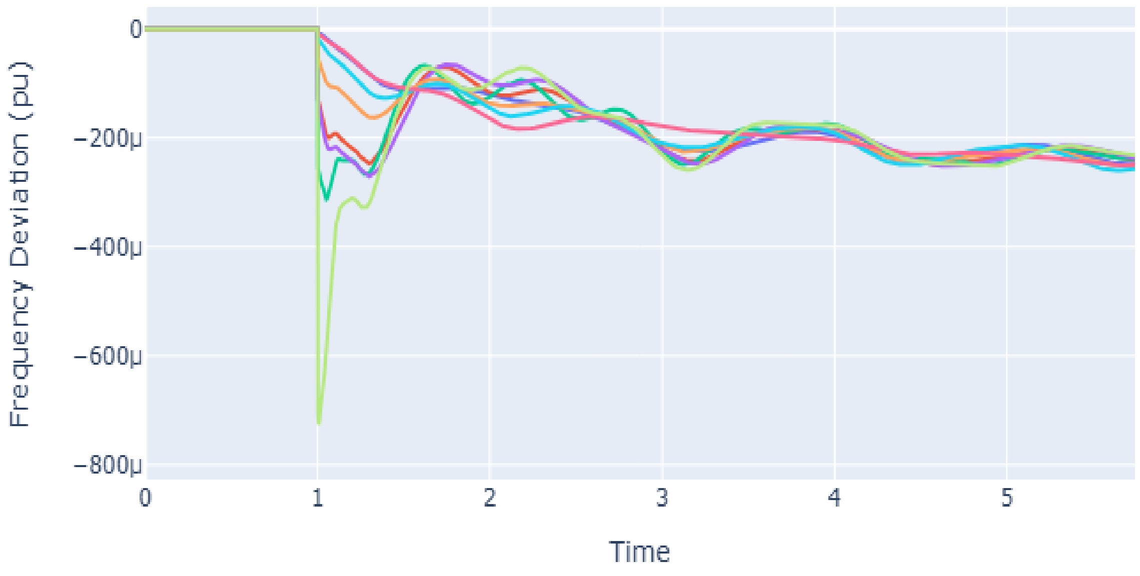


Transmission – Gen Trip Comparison

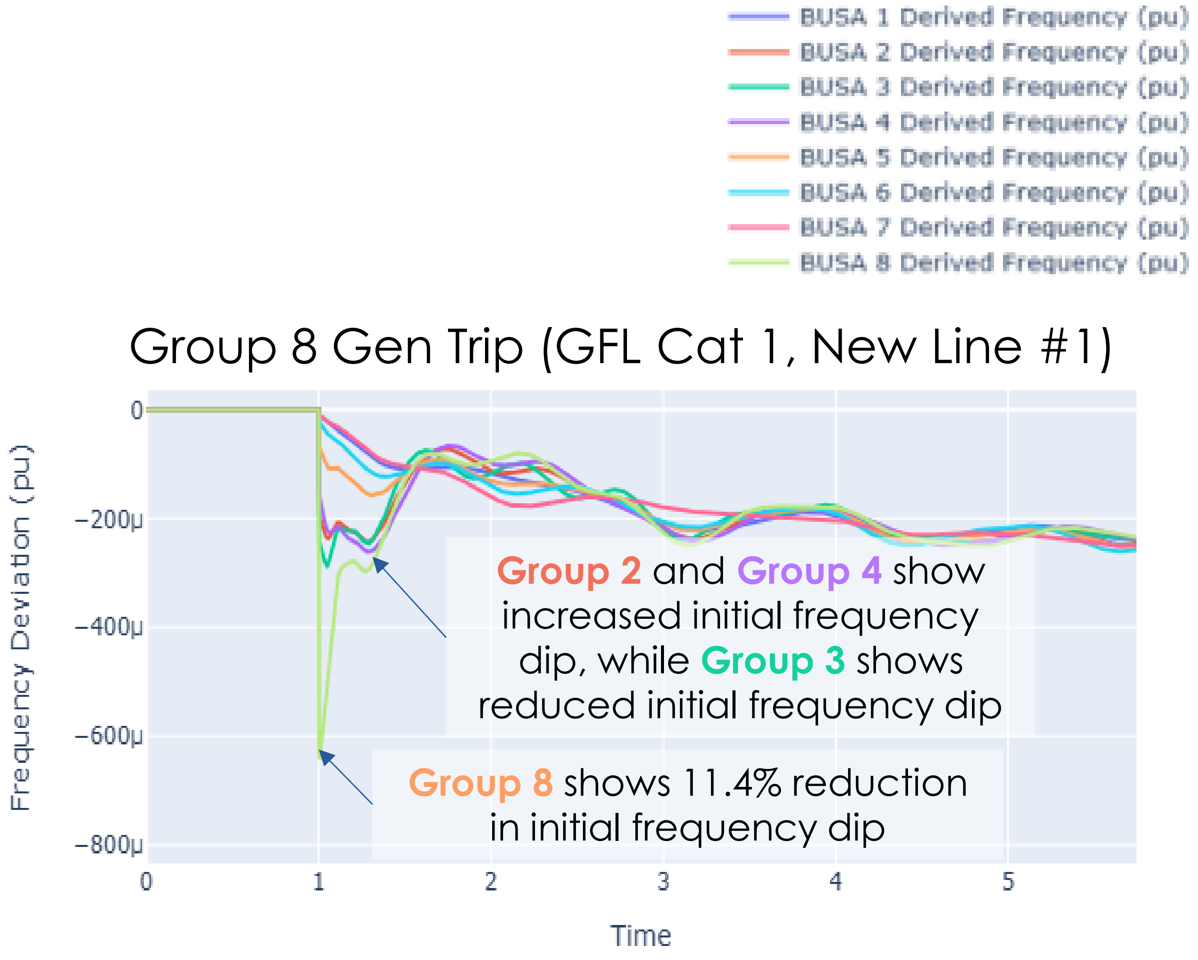
GFL (Category 1) Dominant Case

Loss of 208 MW Generator in Group 8 - Transmission Sensitivity #1

Group 8 Gen Trip (GFL Cat 1)



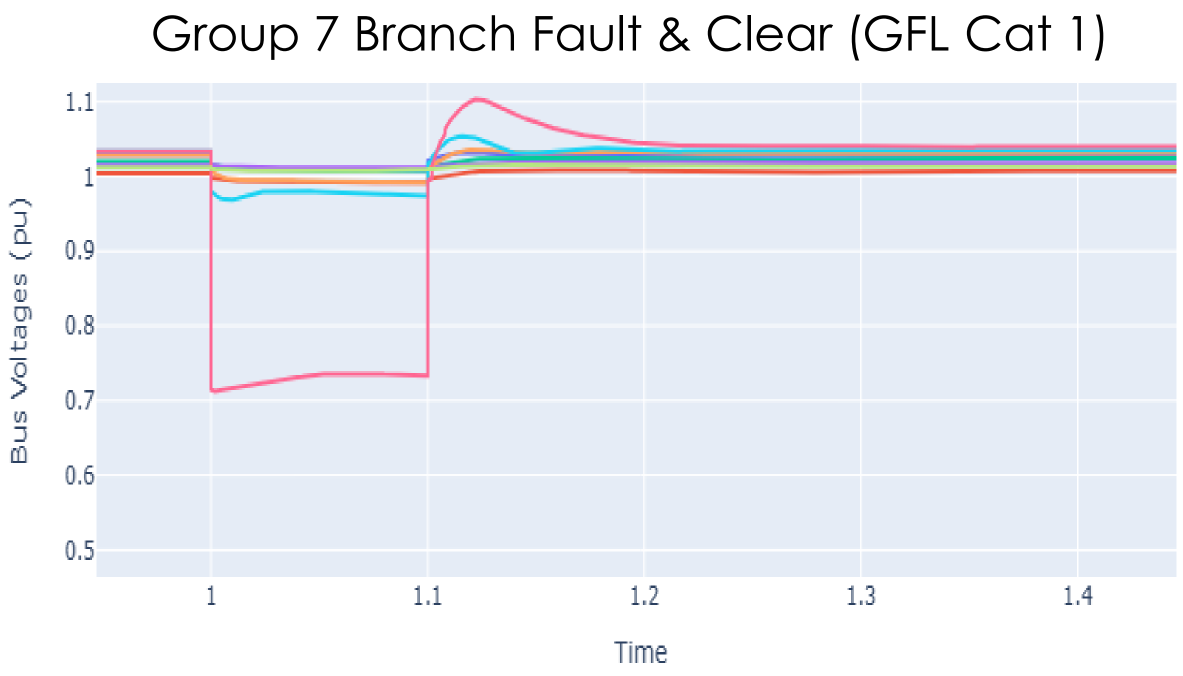
Group 8 Gen Trip (GFL Cat 1, New Line #1)

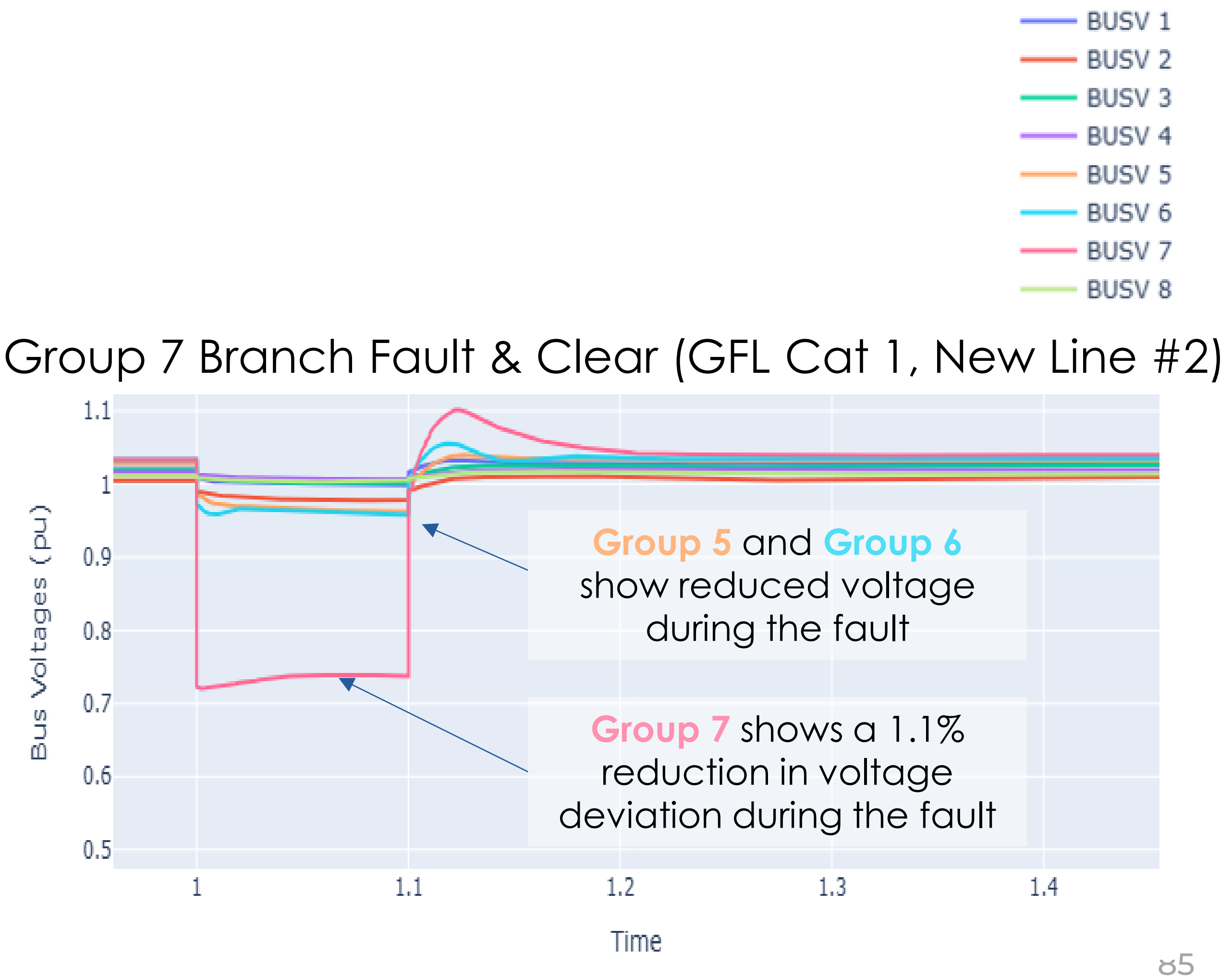


Transmission – Branch Fault & Clear Comparison

GFL (Category 1) Dominant Case

Branch Fault & Clear in Group 7 - Transmission Sensitivity #2



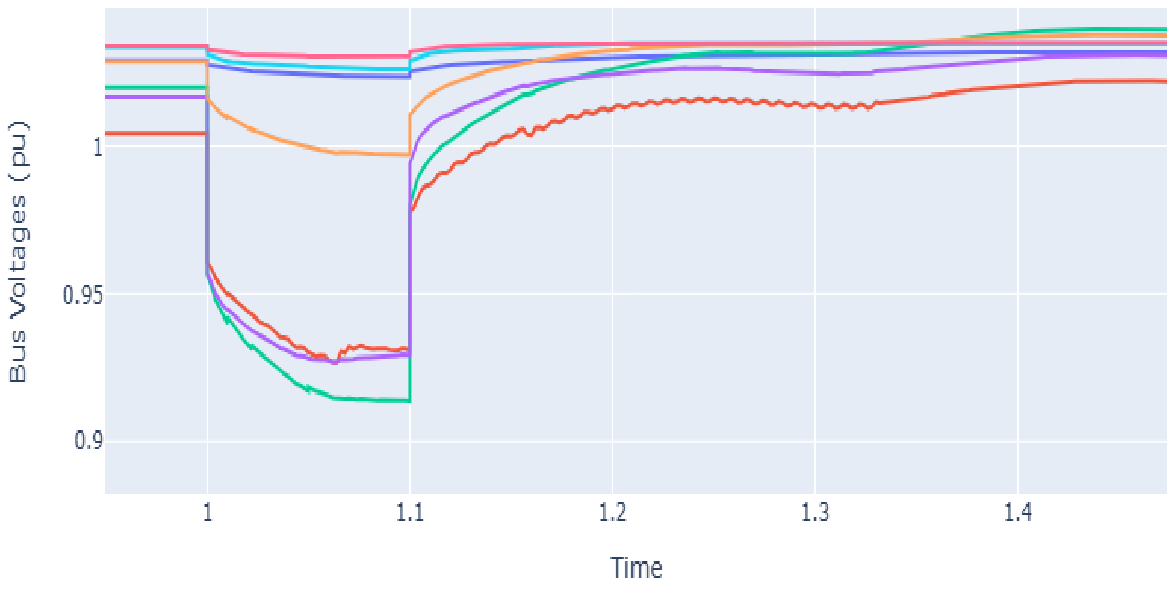


Transmission – Branch Fault & Clear Comparison

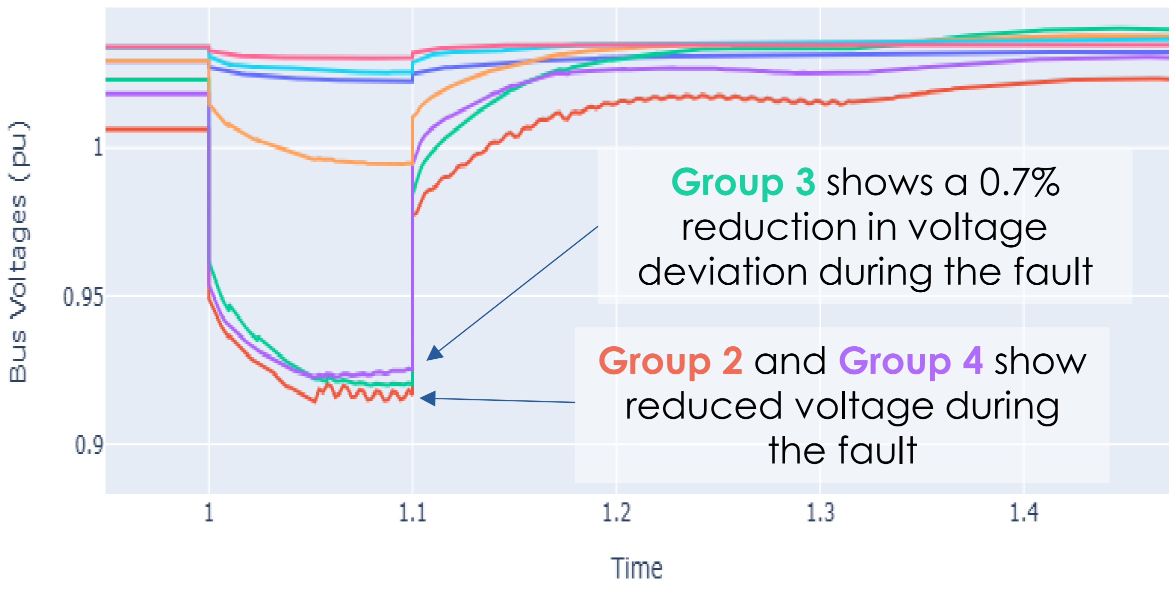
GFL (Category 1) Dominant Case

Branch Fault & Clear in Group 8 - Transmission Sensitivity #1

Group 8 Branch Fault & Clear (GFL Cat 1)



Group 8 Branch Fault & Clear (GFL Cat 1, New Line #1)



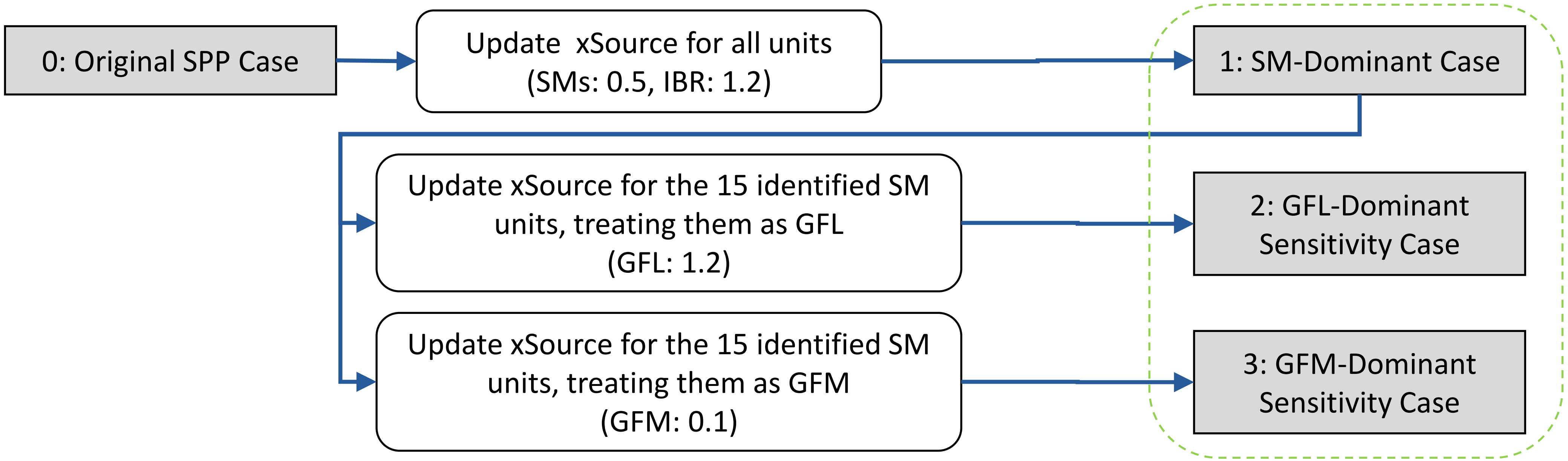
Regrouping the Sensitivity Cases

ESIG
ENERGY SYSTEMS INTEGRATION GROUP

Re-calculating Interaction Factors for the Sensitivity Cases with Dynamic Impedance

- The Dynamic Impedance Method[1] (developed with MISO in 2023) was applied to the case to capture the dynamic behavior (fast reactive power services) by resource type (SM, GFL, GFM)
- The XSORC value (used for the IEC60909 fault calculations) was updated for each resource before proceeding with the interaction factor calculations and grouping algorithm
- This was done because the XSORC values for IBR in today's databases are unreliable

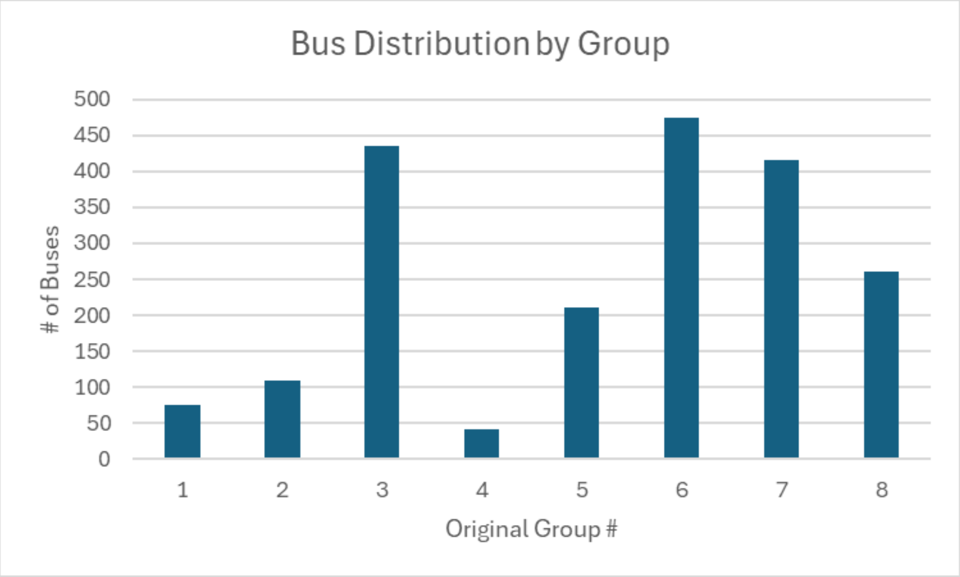
Resource Type	xSource
SM	0.5
GFL	1.2
GFM	0.1



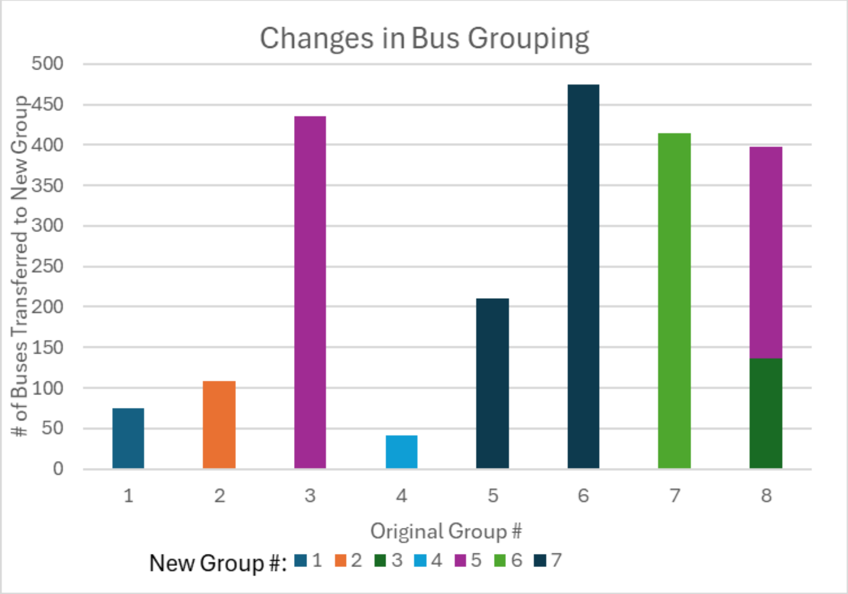
[1] M. P. Richwine, N. W. Miller, A. J. Siler, H. T. Jung and P. Dalton, "Power System Stability Analysis & Planning Using Impedance-Based Methods", Energynautics 22nd Wind & Solar Integration Workshop, Copenhagen, 2023.

Applying the Grouping Algorithm with DZM

- Running the grouping algorithm with they Dynamic Impedance Method (DZM) applied shows some changes
- Changes are due only to an update resource representation
- Resource mix and topology was unchanged



Initial Grouping
(0: Original SPP Case, SM-dominant)

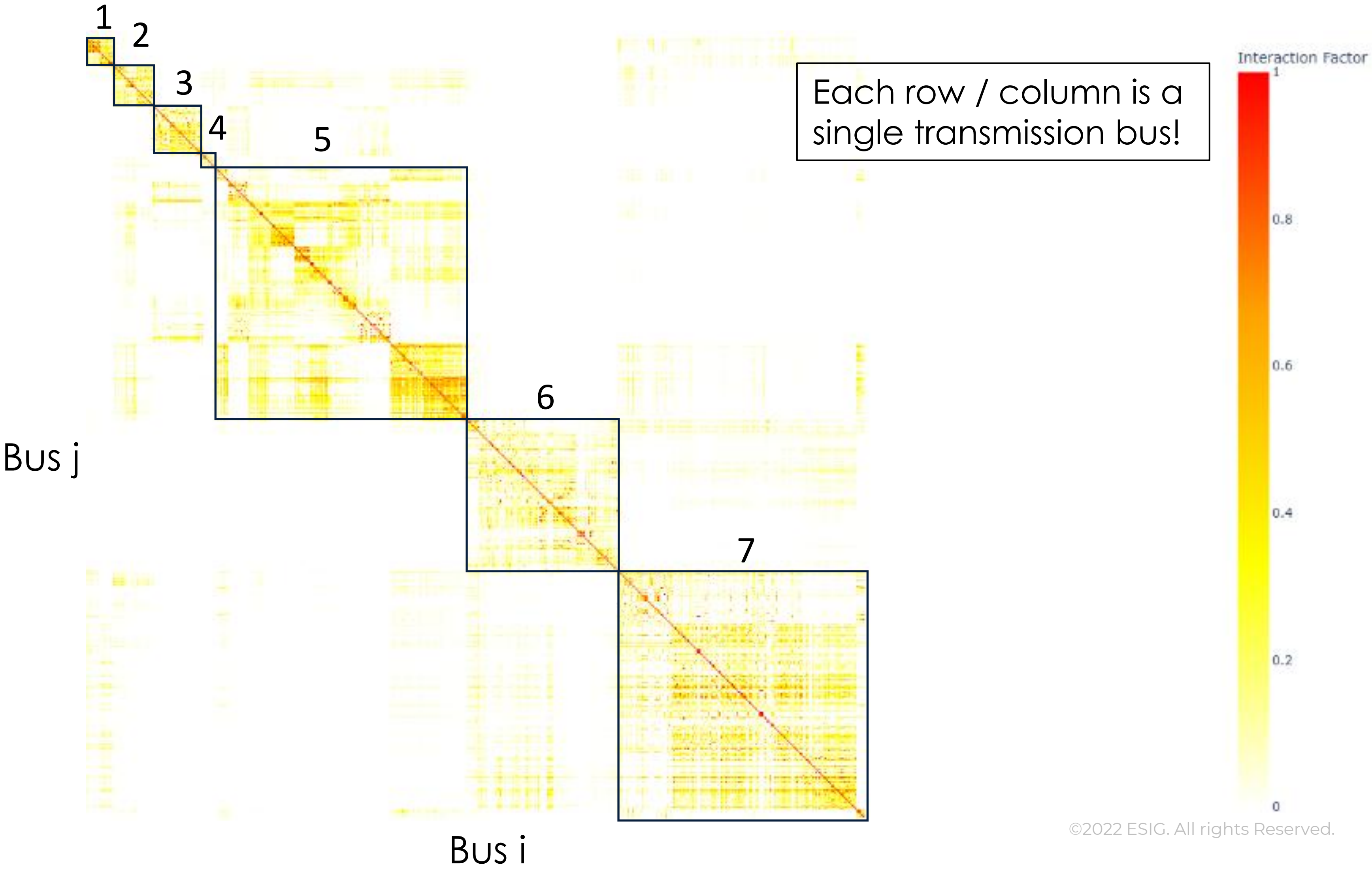


New Grouping with the Dynamic Impedance Method
(1: SM-Dominant Case)

Bus Interaction Factor Matrix with DZM
SM-Dominant System

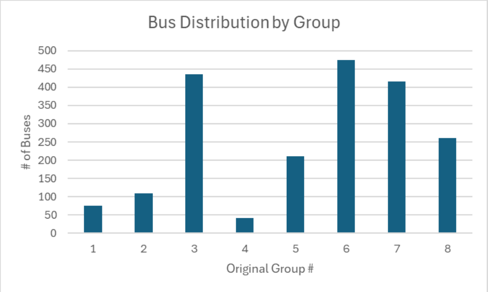
Analyzing the Results with DZM

- 7 groups are formed (down from 8 groups)
- As resource (SM and IBR) XSORC values are increased, it reflects providing less fast-acting voltage support
- Therefore, interaction factors tend to increase, indicating that more transmission buses move together

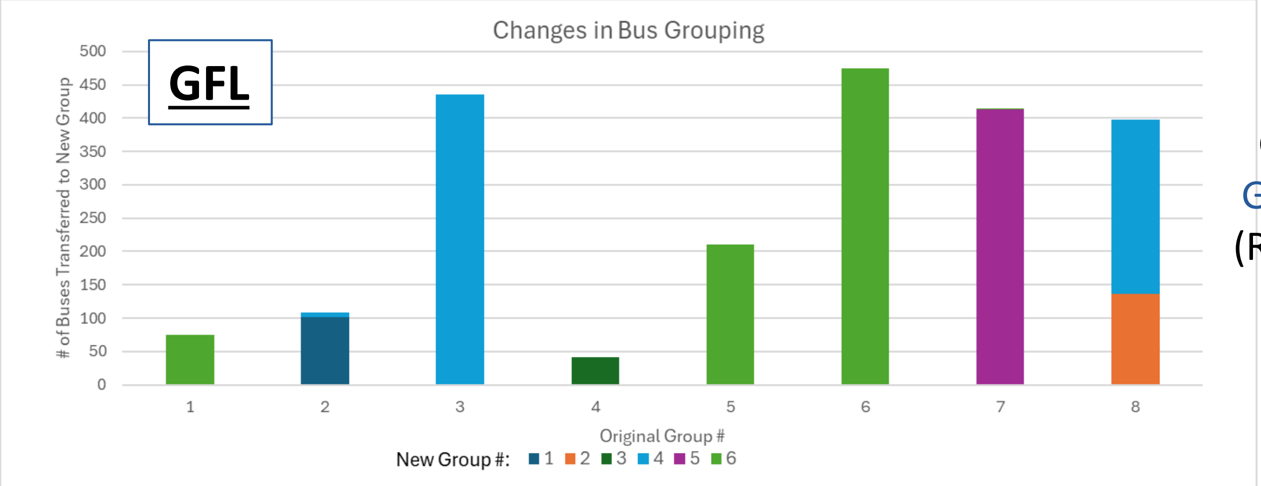


Applying the Grouping Algorithm

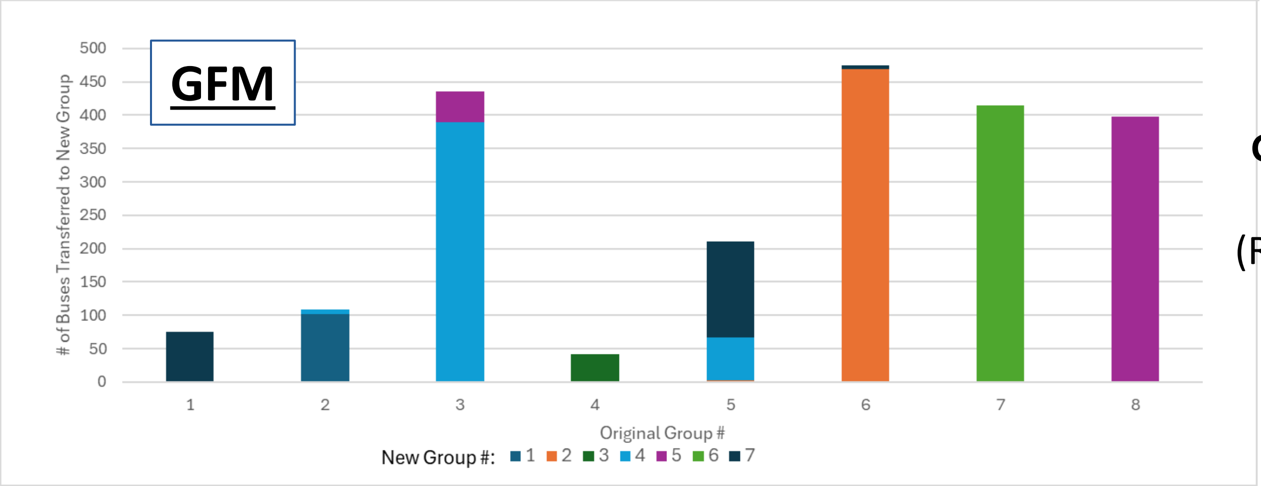
- The grouping algorithm was re-run for each new resource mix sensitivity
- It includes using the DZM
- Changes are due only to changes in resource mix
- Topology was unchanged



Initial Grouping
(0: Original SPP Case)



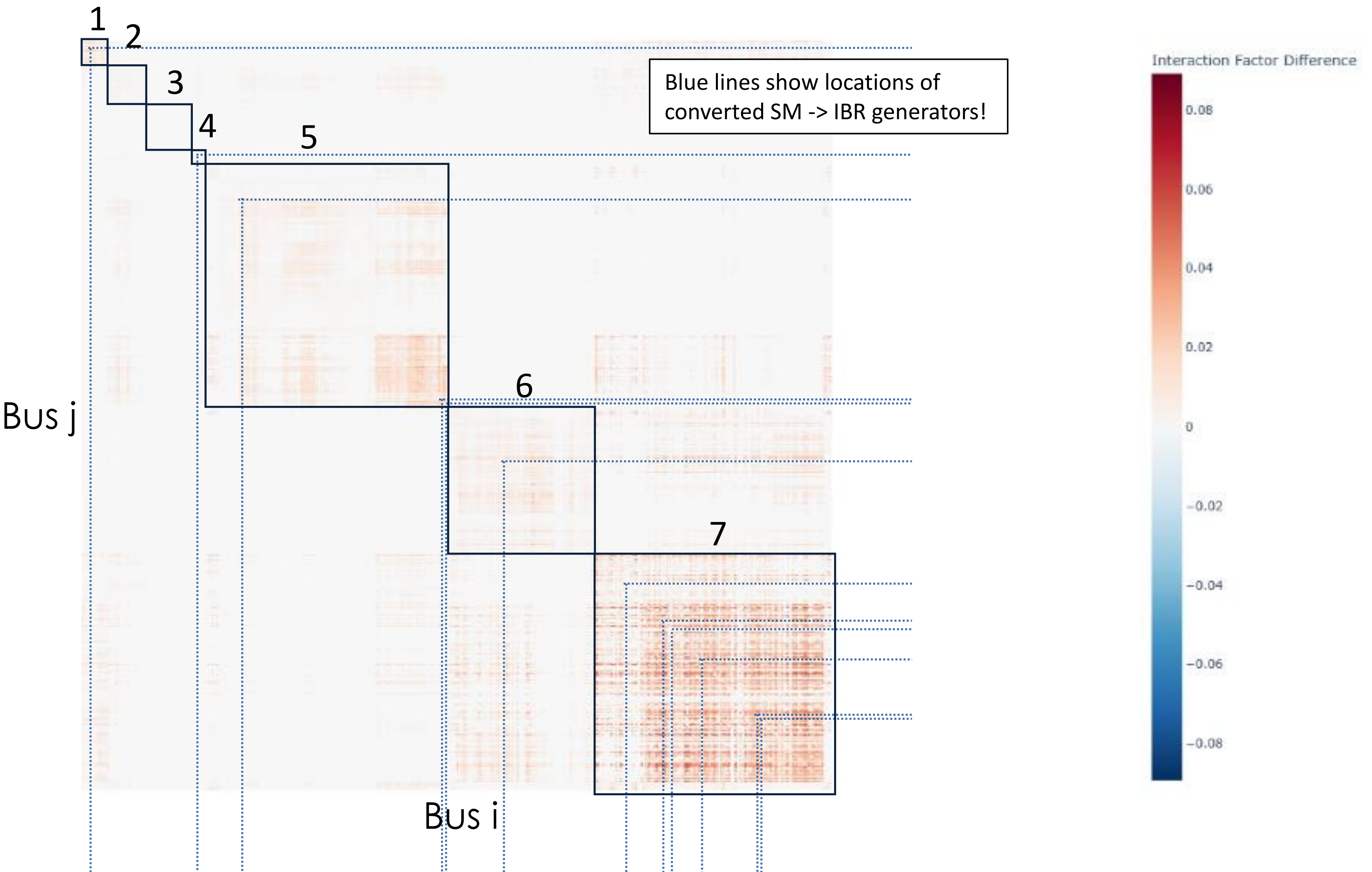
GFL-Dominant Case
Groups tend to merge
(Reasons are discussed next)



GFM-Dominant Case
Groups tend to split
(Reasons are discussed next)

Bus Interaction Factor Difference Matrix

SM -> GFL Dominant System



Less reactive support from GFL Resources

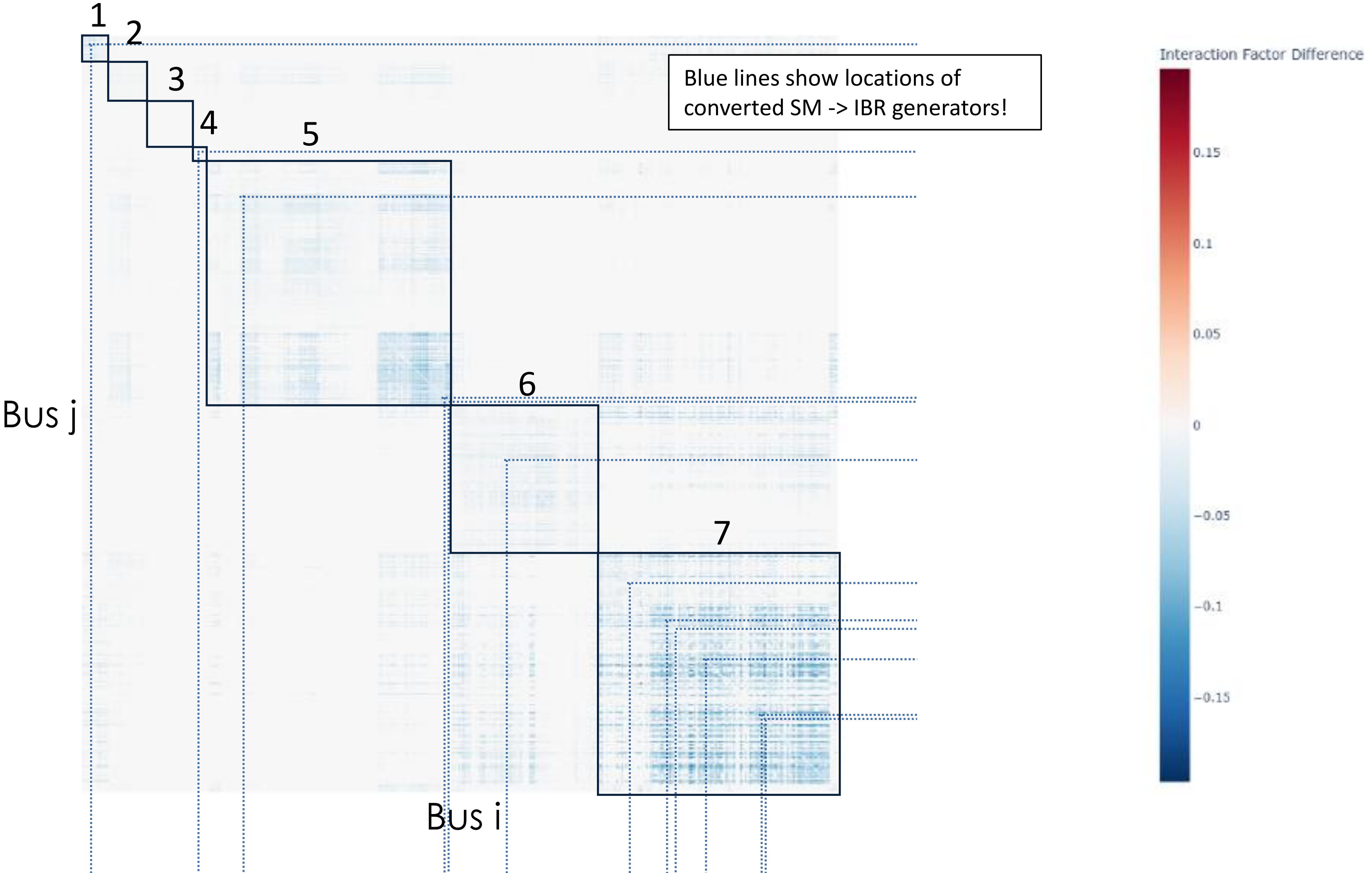
Higher interaction factor between buses

Low system strength - buses are more prone to "swing together"

Increased propagation of stability disturbances

Bus Interaction Factor Difference Matrix

SM -> GFM Dominant System



More reactive support from GFM Resources

Lower interaction factor between buses

High system strength - buses are less prone to "swing together"

Decreased propagation of stability disturbances

Conclusions

Framework Summary

The Services Framework is:

- A new way to evaluate system stability risks and future needs in a way that is:
  - Technology-agnostic
  - Systematic and repeatable
  - Scales for large and small systems
- Much faster than system-level dynamic simulation → enables engineers to evaluate more futures & operating conditions efficiently
- Utilizes existing tools and data -- power flow cases and dynamic databases

Appropriate Framework → Efficient Analysis → Effective Planning

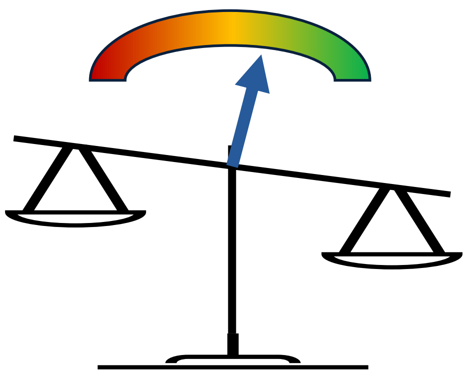
Lessons Learned

Lessons Learned

- Most resources provide valuable stability services, regardless of technology;
  - The key is which services, how much, and how much is needed at that location?
- Dynamic model quality is foundational and continues to be a challenge
- Appropriate analysis of fast time-frames is tricky! i.e., signals measuring “frequency” need to be treated with great care

Next Steps

- Improve data checking during data intake of dynamic models
- Establish guidelines for acceptable performance → (What ratio of provision-to-need is appropriate for each service)
- We are pursuing more regions for applying this framework!



Dynamic Stability Assessment Approaches

for Large System Models

Current Practice

Time-consuming to setup and run

people + computation

Results are narrow

for a specific operating condition

Uncertainty in future resource performance

details of resource models are likely to change anyway

Requires **intensive investigation** of issues

often hard to diagnose root causes, prepare mitigations

Our Services Framework

Quick evaluations after setup

setup leverages current practices

Speed lets **more grid conditions** be studied

handle the increased variability of grid operations & futures

Captures **essential performance** of resources

Focus on the most important aspects; less likely to change

Faster identification of risks & mitigations

quickly determine nature & location of risks → mitigations

Framework Applications

- Highlight in future scenarios / resource portfolios where there are "**weak pockets**" lacking sufficient services
- Inform how **transmission investments** may be located to deliver energy AND stability services
- Identify **potential plant retirements** that would likely to cause stability problems
- Inform where **Grid-Forming (GFM) inverter technology** should be strategically located, and how much, what reserves to maintain
- Show how **changing grid operations** (even within a day/week/seasonal) can impact the level of services and therefore, stability

Applications for Planning

Applications for Operations

Industry Cross-Pollination

- Throughout 2024, monthly “Services Task Force” meetings for industry professionals focused on stability and services, including system operators, consultants, and researchers
- At each meeting, (a) progress updates presented on this work seeking feedback and (b) system operators presented their work on grid services

Session	Contributor	Organization
April 16	ESIG Webinar	Telos/HickoryLedge/EPRI
May 20	TF Kick-Off	ESIG et al.
June 17	Fatemeh and Ambuj	Imperial College of London
August 19	Mostafa Sedighizadeh	SPP
September 16	Xiaoyao Zhou	NationalGridESO
October 21	ESIG Fall Technical Workshop	n/a
November 18	Nitika Mago	ERCOT
December 16	Patrick Dalton	MISO

Outreach & Public Documents

ESIG Services Task Force, on-going monthly meetings

SPP, MISO, TVA, NationalGridESO, FERC

ESIG Webinar, April 2024

A Framework for Quantifying Supply and Demand for Grid Stability Services

Wind & Solar Integration Conference Paper, September 2024

Framework to identify and evaluate dynamic performance characteristics of IBRs in a transmission network

ESIG Technical Workshop Presentation, October 2024

Wind & Solar Integration Workshop Paper, October 2024:

Framework to Identify and Evaluate Dynamic Performance Characteristics of Inverter-Based Resources in a Transmission Network

NERC Inverter-Based Resource Subcommittee, Late 2024 / Early 2025

ESIG Webinar, Early 2025 (Planned)

A Tweaked Paradigm

There is no fundamental limit to IBR with currently-available technology IF accompanied by:

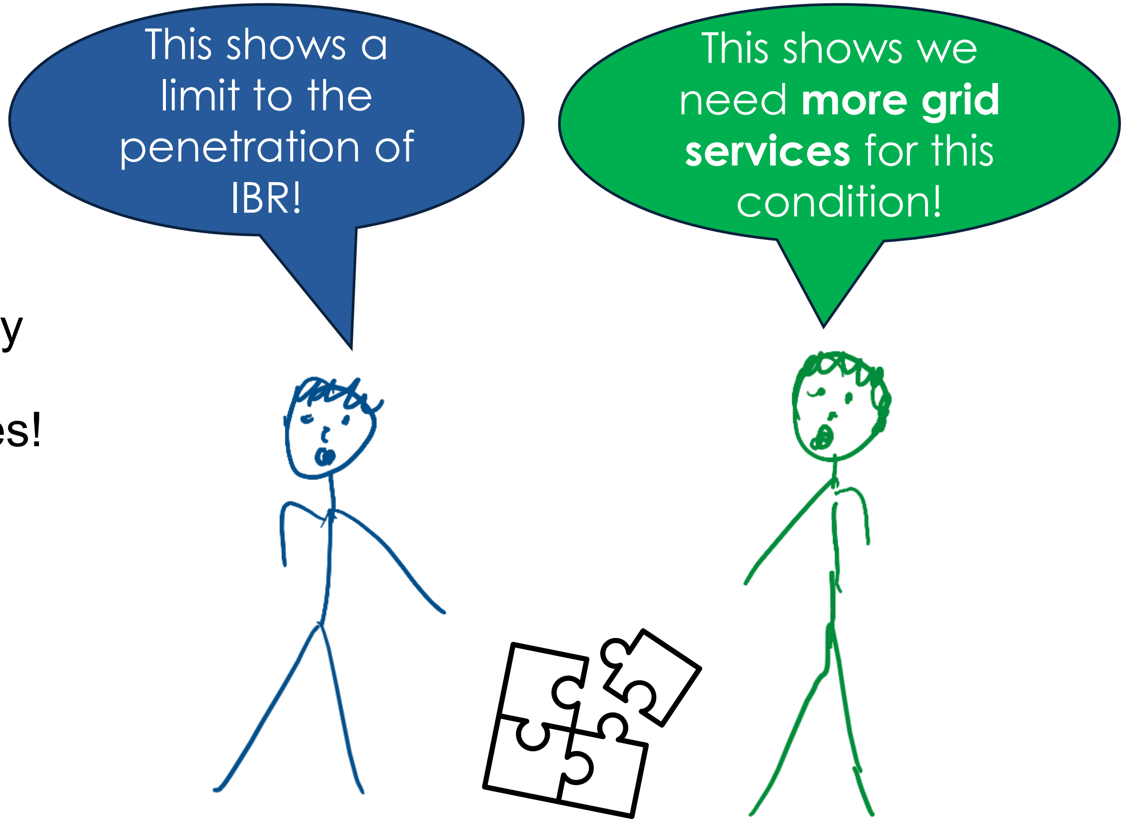
- appropriate changes to operations
- installation of appropriate enabling hardware and controls

It is a matter of providing locationally sufficient & timely stability services on any grid to cover all planned operating conditions. The changes described above enable that provision of services!

Services should be

- rigorously defined,
- technology-agnostic, and
- systematically quantified.

This framework should be applicable for all grids.



Appropriate Framework → Efficient Analysis → Effective Planning

Future Work

- Consideration of improved GFL resources
- Refinement of resource characterization method, particularly for fast active power
- Populating the “medium-speed” services buckets
- Better tie framework results to absolute metrics and acceptance criteria
- Predicting new transmission impact based on services and the interaction factor matrix
- Optimize locations for resources based on findings of provision and need
- Examine relationship between services, grid strength, and short circuit MVA
- Consideration for damping services
- Consideration for fault-current services
- Handling of study area boundary
- …

THANK YOU