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# A Stability Analysis Framework for Oscillation Analysis and Mitigation

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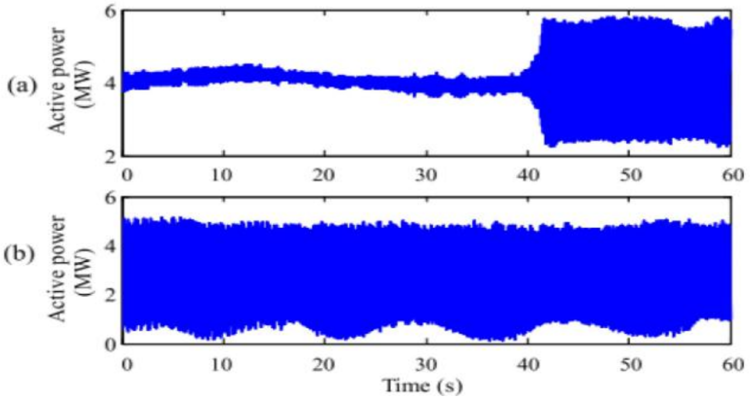
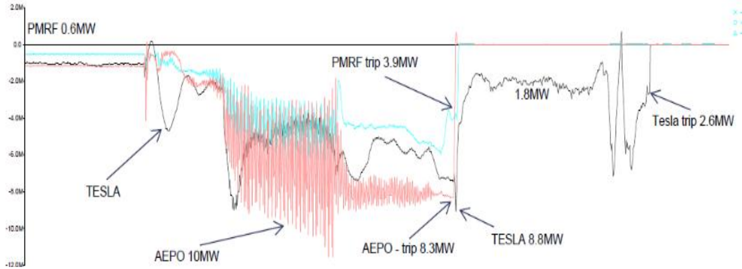
*Photo by Josh Bauer, National Laboratory of the Rockies 61725*

# Background

- Power system stability has become a significant concern to all energy stakeholders because of ever-increasing Inverter Based Resources (IBRs)
- IBR driven stability causes significant damage to the power system
- The stability challenges may ***become more significant*** in the future when IBRs become dominant in power systems
- **Grid operators need tools to identify the stability issues and find mitigation solutions**.

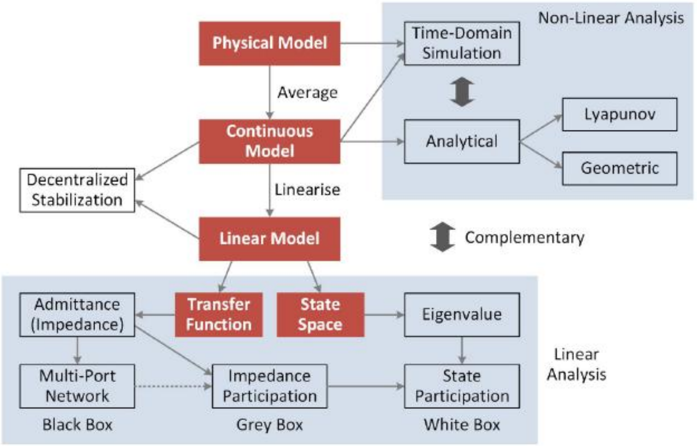


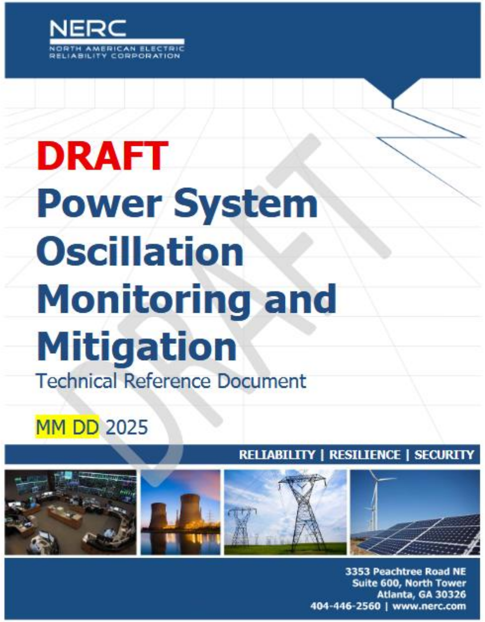




*Credit: KIUC*

[1] Y. Chen, et al., "Real-World Subsynchronous Oscillation Events in Power Grids with High Penetrations of Inverter-based Resources," IEEE. Tran. Power System, vol. 38, no. 1, Jan. 2023.

# Motivation/Goal




- Provide good information of oscillations
- Lack of insights on how to mitigate those issues
  - Some methods can't provide those information (scratch the surface of the problems)

- A methodology and framework that based on the power system models and dynamics
  - Gives insight to the effect of parameters, setpoints, etc.
- Scalable to large systems
  - Realistic for utilities to use
- Quick and simple to use

- Run as an analytic digital twin model for grid operator to pinpoint the stability issue and mitigate solutions

# An Overview of The Framework

## Data Input

*Automated Parsing*

IBRs, Generators, Network

→

## Power Flow

*Fast - Find Operating Point*

→

## Automated Differentiation

*Allows for generating devices across the system to be connected*

$$\frac{df}{dx} = \begin{bmatrix} \text{GFL1} & & & & & & & & \\ & \text{GFL2} & & & & & & & \\ & & \cdots & & & & & & \\ & & & \text{GFM1} & & & & & \\ & & & & \text{GFM2} & & & & \\ & & & & & \cdots & & & \\ & & & & & & \text{SG1} & & \\ & & & & & & & \text{SG2} & \\ & & & & & & & & \cdots \end{bmatrix}$$

↓

## System-Wide Model

*Perform matrix math to express the entire system as a single, standalone equation*

$$\frac{dx}{dt} = Ax$$

←

## Parameter Sensitivity

*Assess parameter's impact on the properties of A*

$\frac{d\lambda}{d\eta}$ → How to best change η so oscillations damp out?

←

## Applications

Stability indication

Oscillation detection

Identify cause of oscillation

Mitigate oscillation (e.g., control parameter tuning)

**This small-signal based stability framework is fully automated!**

# Example Test System

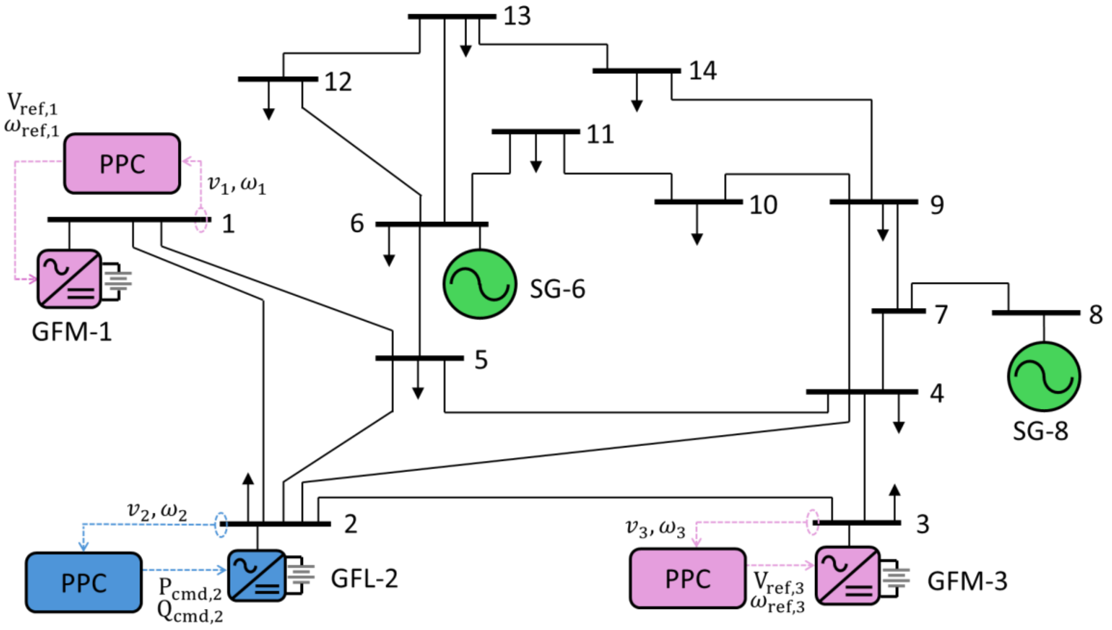



TABLE I
MODAL ANALYSIS RESULTS - UNTUNED

| Mode | Frequency (Hz) | Damping Ratio | Largest Participating States |
|---|---|---|---|
| $\lambda_1$ | 7.141 | 0.0340 | $\delta_1,\ \omega_1,\ \delta_3,\ \omega_3$ |
| $\lambda_2$ | 3.134 | 0.1578 | $\omega_3,\ \delta_3,\ \omega_1,\ \delta_1,\ P_{cmd,2},\ \delta_2,\ \delta_6,\ \omega_6$ |
| $\lambda_3$ | 1.725 | 0.1067 | $\omega_6,\ \delta_6,\ \omega_8,\ \delta_8$ |
| $\lambda_4$ | 0.915 | 0.0175 | $\delta_2,\ \epsilon_{p,2},\ P_{cmd,2},\ \omega_8,\ \delta_8,\ \omega_6,\ \delta_6$ |
| $\lambda_5$ | 0.410 | 0.1457 | $E_{fd,8},\ E_{q,p,8},\ V_{f,8}$ |
| $\lambda_6$ | 0.260 | 0.6205 | $V_{f,6},\ E_{q,p,6},\ E_{fd,6}$ |

Possible Oscillation Frequencies

Amount of Damping of Those Oscillations

Variables Within Devices Responsible for the oscillations

- We first apply this framework in a 4-bus system and then 14 bus system (2 GFM, 1 GFL and 2 SG)
- PPC is also included for each IBR
- 45 states included in the A-matrix

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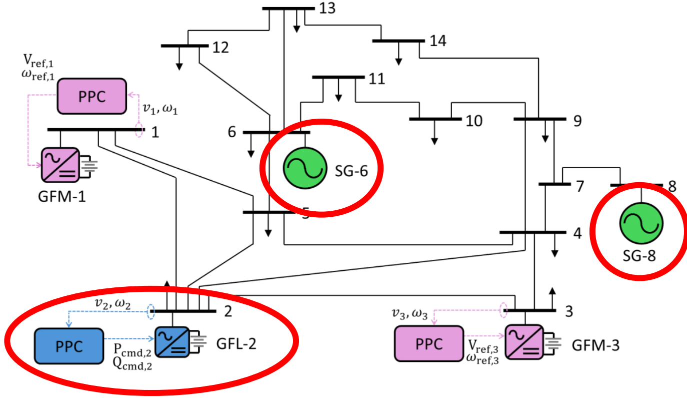
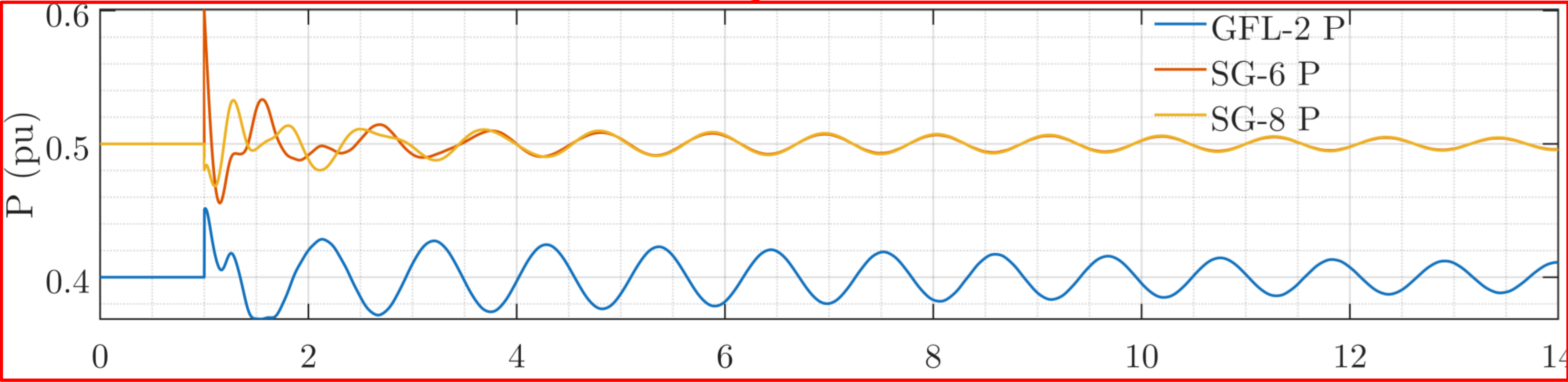
The participation factors told us *beforehand* these devices would be involved in this oscillation




The GFL and 2 Synchronous Generators are seen to oscillate at the 0.915 Hz frequency – very poorly damped!



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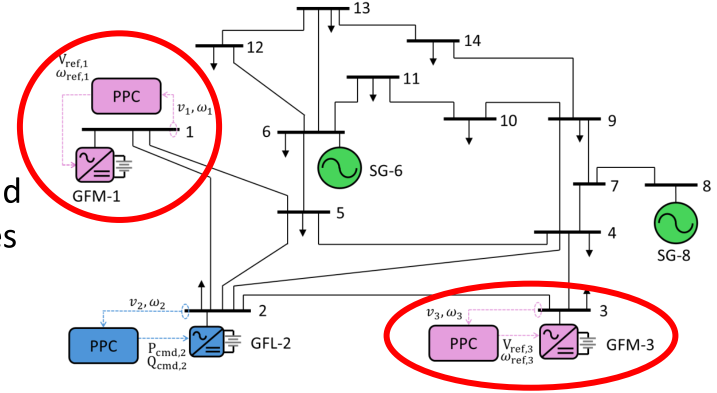
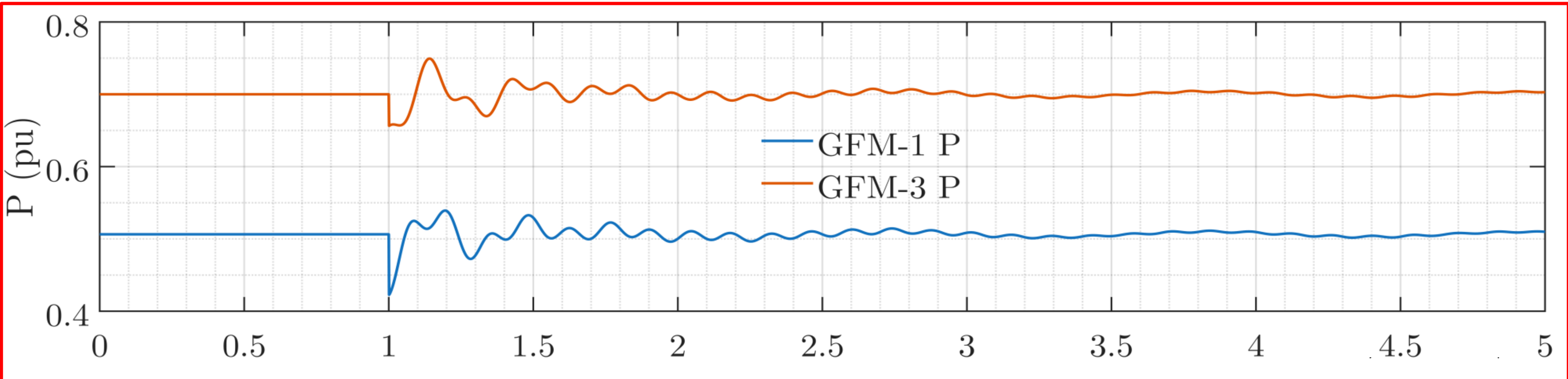
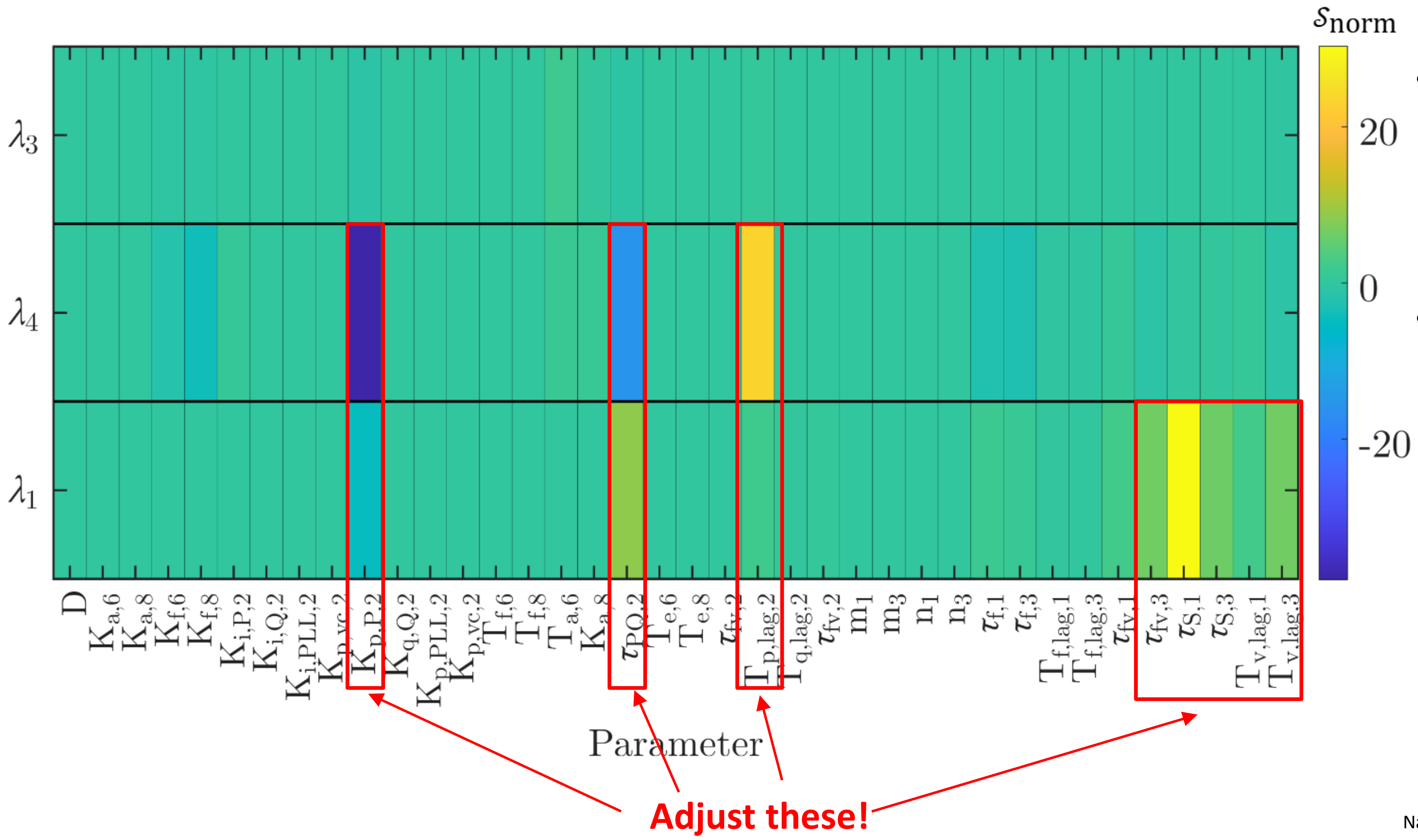



The 2 GFMs are seen to oscillate at the 7.141 Hz frequency – also poorly damped!



# Parameter Sensitivity




- Pinpoint the parameters need to be tuned and direction to be tuned
- If the color shows negative which means the parameter needs to be increased.

# Tuning Parameters

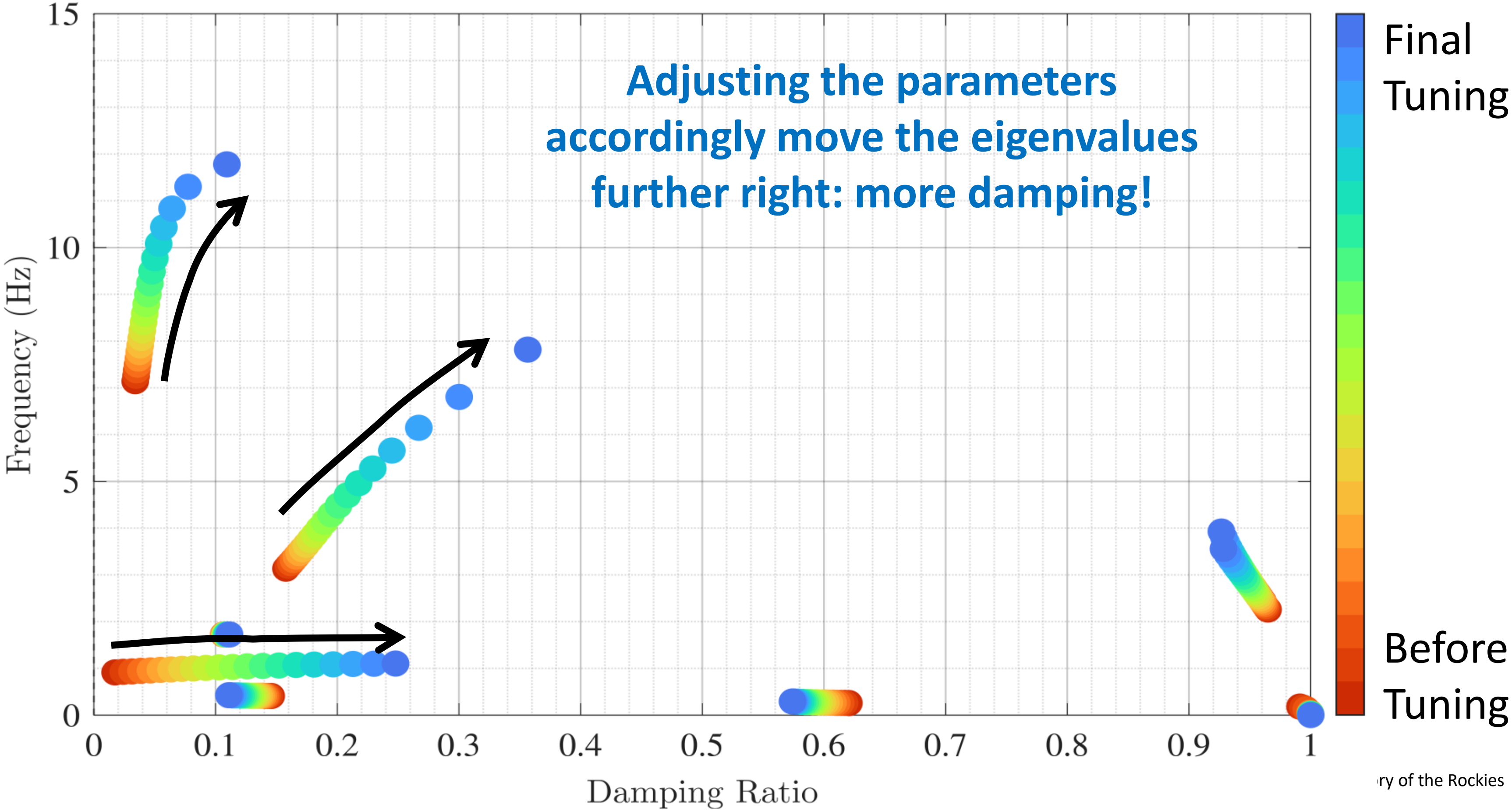


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TABLE II
MODAL ANALYSIS RESULTS - TUNED

| Mode | Frequency (Hz) | Damping Ratio | Largest Participating States |
|---|---|---|---|
| $\lambda_1$ | 11.779 | 0.1092 | $\omega_1, \delta_1, \omega_3, \delta_3$ |
| $\lambda_2$ | 7.816 | 0.3566 | $\omega_3, \delta_3, \delta_2, \omega_1, \delta_1, P_{cmd,2}$ |
| $\lambda_3$ | 1.725 | 0.1114 | $\omega_6, \delta_6, \omega_8, \delta_8$ |
| $\lambda_4$ | 1.102 | 0.2480 | $\omega_8, \delta_8, \delta_2, \epsilon_{p,2}, \omega_6, \delta_6$ |
| $\lambda_5$ | 0.427 | 0.1109 | $E_{fd,8}, E_{q,p,8}, V_{f,8}$ |
| $\lambda_6$ | 0.293 | 0.5742 | $V_{f,6}, E_{fd,6}, E_{q,p,6}$ |

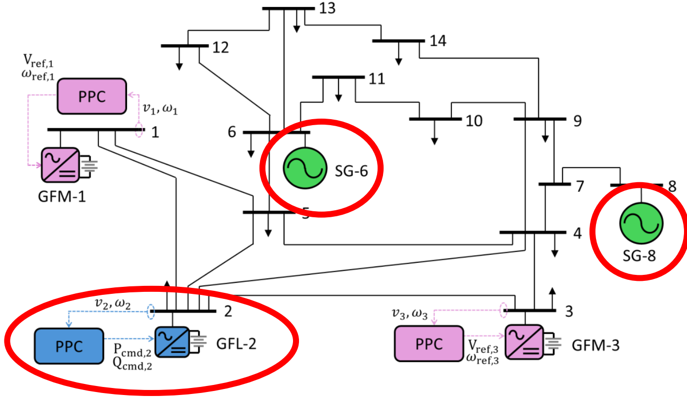
**Much higher damping!**

CONTROLLER PARAMETER TUNING RESULTS

| | $\tau_{PQ,2}$ | $K_{p,P,2}$ | $\tau_{ff,2}$ | $T_{p,lag,2}$ | $\tau_{fv,2}$ | $\tau_{s,1}$ | $\tau_{s,3}$ | $\tau_{ff,1}$ | $\tau_{ff,3}$ | $\tau_{fv,1}$ | $\tau_{fv,3}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Initial Value | 0.05 | 0.5 | 0.05 | 0.2 | 0.03 | 0.23 | 0.23 | 0.1 | 0.1 | 0.03 | 0.03 |
| Final Value | 0.01 | 0.9 | 0.02 | 0.02 | 0.01 | 0.1 | 0.1 | 0.02 | 0.02 | 0.02 | 0.02 |

**We may know what to be tuned but we don't know how to tune them without this framework!**

# Tuned Test System

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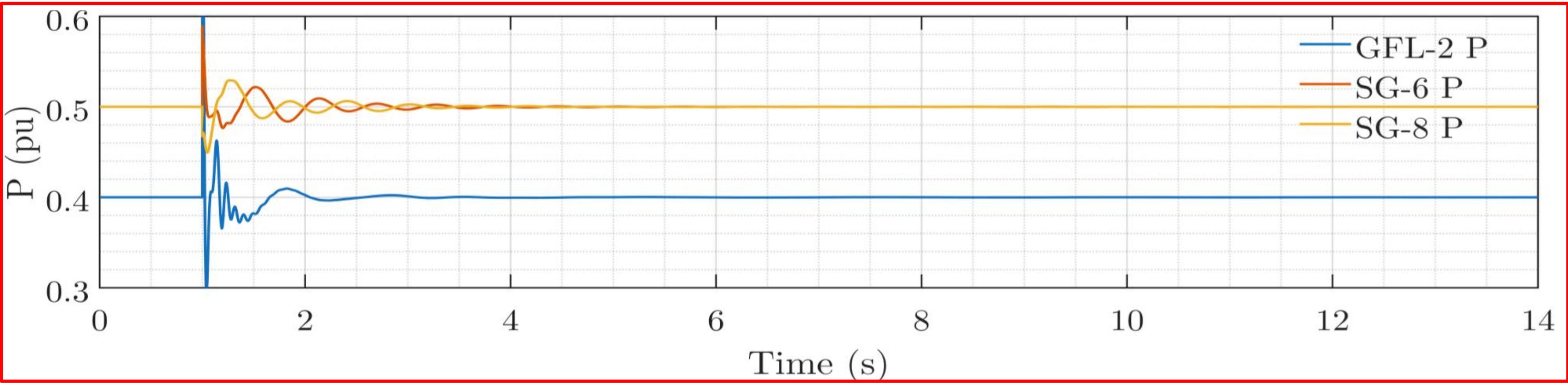

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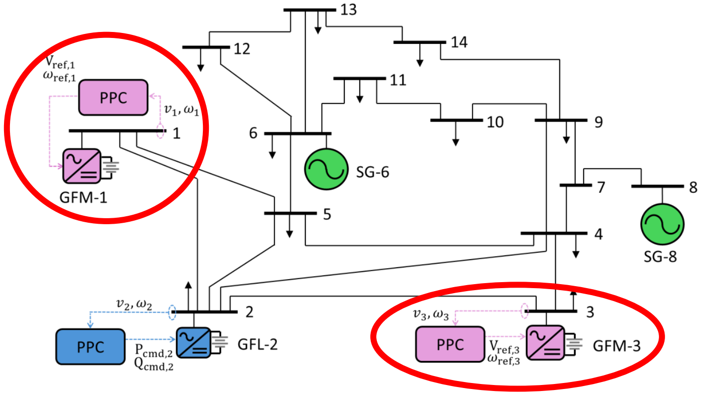
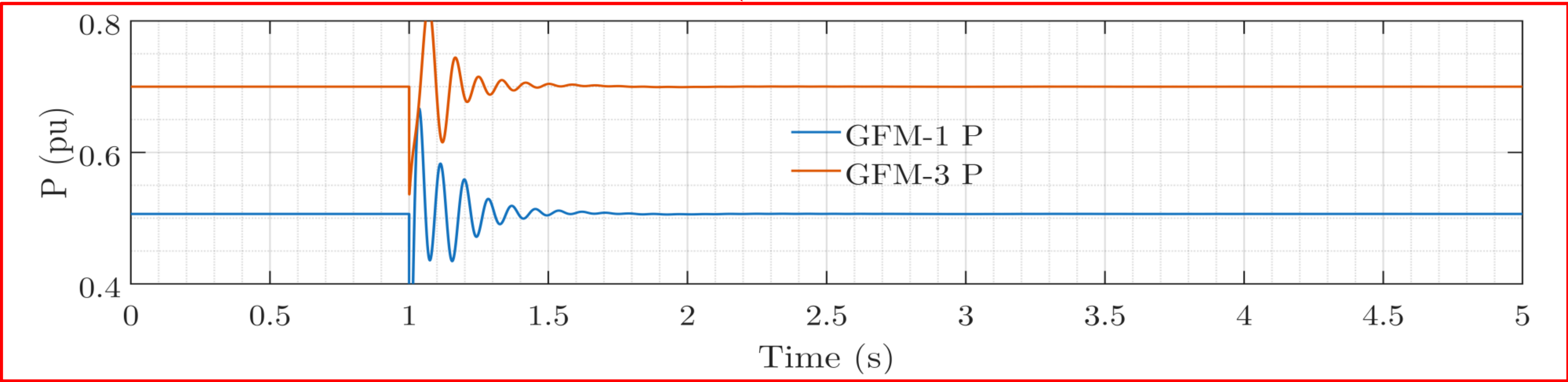



The 2 GFMs are seen to stop oscillating much faster than before



# Conclusion

- Small-signal based eigenvalue approach provides rooted-solutions for troubleshooting and mitigating oscillation problems.
  - Include all the key control loops and parameters
  - Develop a system-level stability analytic framework
  - Demonstrate its efficacy with examples
- The fully automated process makes this framework applicable and scalable for any real-word systems
- This framework severs as a foundation for future studies aimed at automated tuning, robust control design or integration of GFM/GFL controls strategies etc.

# References

[1] S. Chakraborty, B. Umathe, J. Wang, “Control Parameter Sensitivity Study for Inverter-Based-Resource Dominated Grids: A Small Signal Stability Approach and Framework,” 2025 IEEE Energy Conversion Conference Congress and Exposition (ECCE).

[2] O. Cornmesser, S. Chakraborty, J. Wang, “Control Parameter Sensitivity Study for Inverter-Based-Resource Dominated Grids: A Small Signal Stability Approach and Framework,” IEEE Tran. Ind. Applications, 2026 (submitted).

# Questions/Answers

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