System Strength Sensitivity to Power Flow Perturbations in AC Power Systems with Inverter-based Resources

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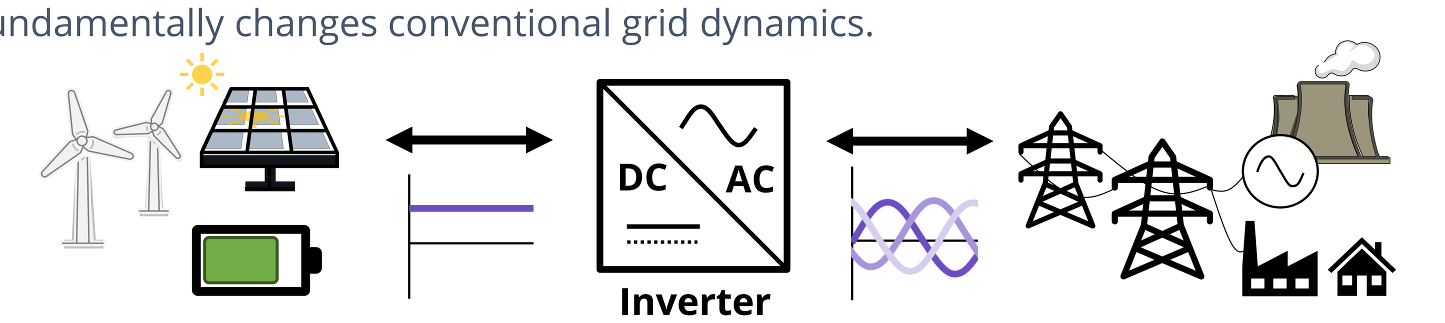
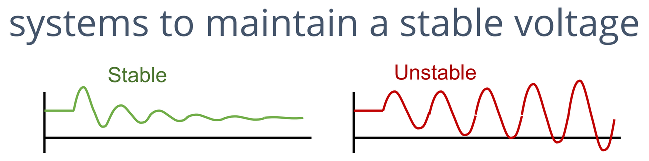
Grid-Interfacing Inverters

- **Inverter-based resources (IBRs)**, such as solar, wind, and batteries, produce direct current (DC) and are interfaced to alternating current (AC) networks through inverters.
- Unlike synchronous generators (SGs), inverters lack physical inertia which fundamentally changes conventional grid dynamics.



Power System Strength

System Strength is the ability of power systems to maintain a stable voltage and frequency under disturbances [1].



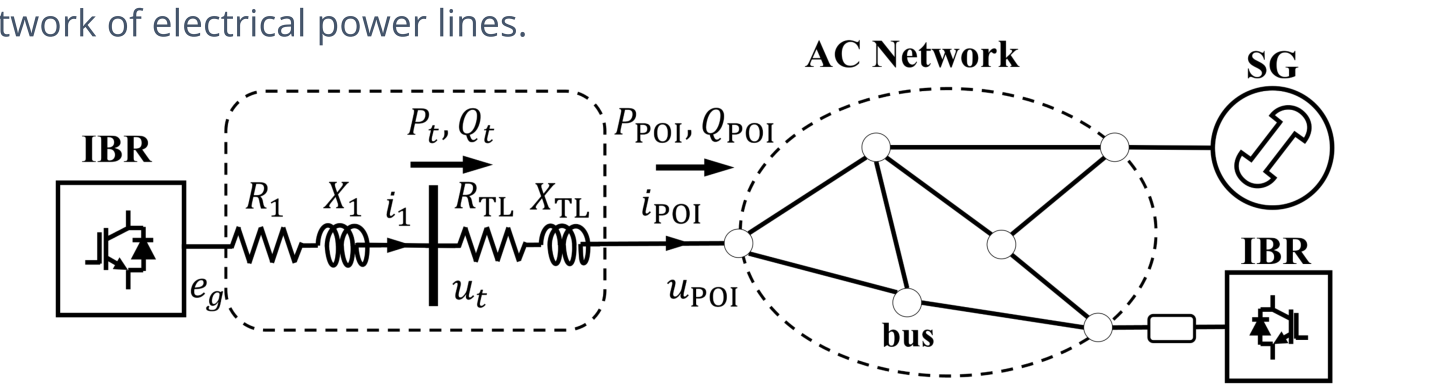
Challenges with System Strength:

- As more IBRs have been integrated into the grid, system strength has decreased.
- Conventional metrics, like the Short-Circuit Ratio (SCR), rely on steady-state fault currents and ignore the dynamics of inverter controls.
- Few system strength metrics provide system operators with clear actionable information to help maintain system stability in real-time.

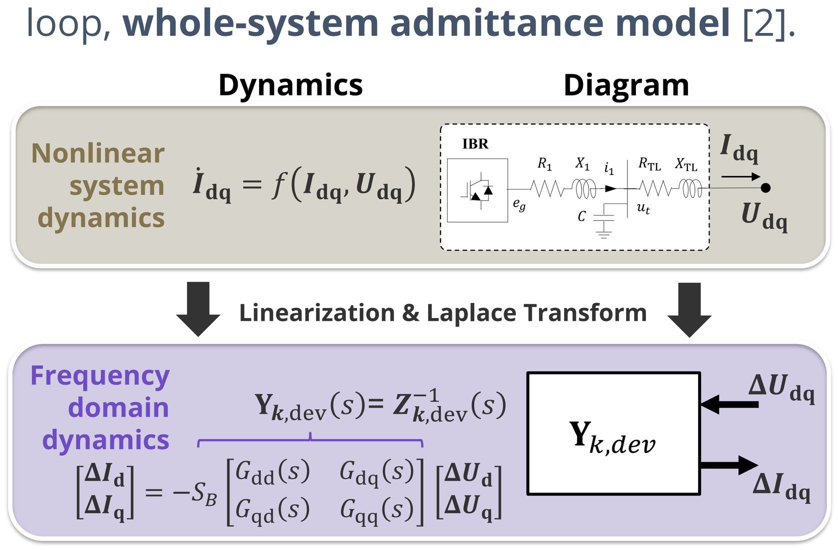
We propose sensitivity indices that trace small-signal stability directly back to specific power injections, highlighting "weak" areas and giving actionable insights.

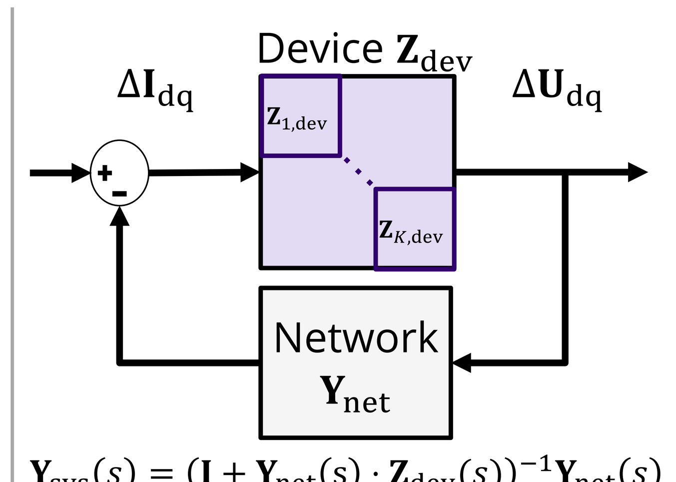
AC Network System Model

- We model a system with K devices (SGs, IBRs, etc.) at N buses connected through an AC network of electrical power lines.



- We model **small-signal system behavior** by linearizing nonlinear device dynamics around a steady-state AC power flow operating point $\mathcal{M} = (\mathbf{P}, \mathbf{Q}, \mathbf{V}, \mathbf{\Theta})$, which represent **equivalent impedance models** in the frequency domain.
- Coupling these device admittances with the network admittance model, yields a closed-loop, **whole-system admittance model** [2].

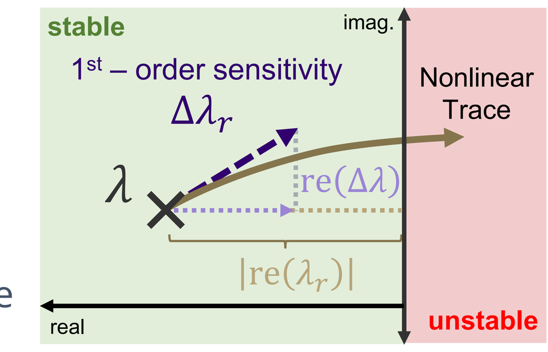




$$\mathbf{Y}_{sys}(s) = (\mathbf{I} + \mathbf{Y}_{net}(s) \cdot \mathbf{Z}_{dev}(s))^{-1}\mathbf{Y}_{net}(s)$$

Small-signal Stability Sensitivity Analysis

- This model allows us to evaluate **if the system is stable, returning to its equilibrium after small disturbances.**
- System stability is determined by its poles; **if all poles reside in the left-half of the complex plane, the system is stable.**
- **First-order pole sensitivities** to device impedances can be derived from the residue of the whole system admittance model and used to explore how susceptible the system small-signal stability is to a perturbation in $\mathbf{Z}_{dev}$ [3].



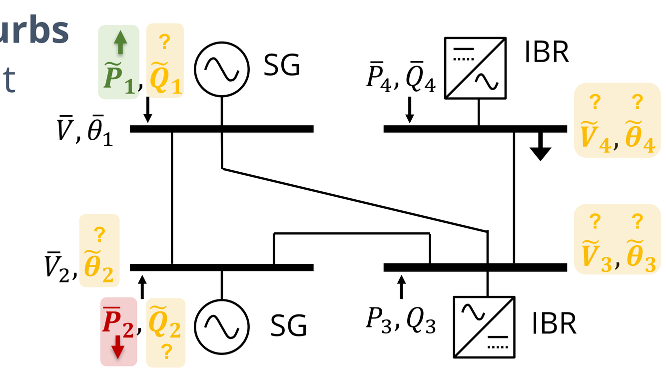
$$\frac{\partial\lambda}{\partial \mathbf{Z}_{k,\mathrm{dev}}(\lambda)} = -\mathrm{Res}_{\lambda}\mathbf{Y}_{kk}^{\mathrm{sys}}$$

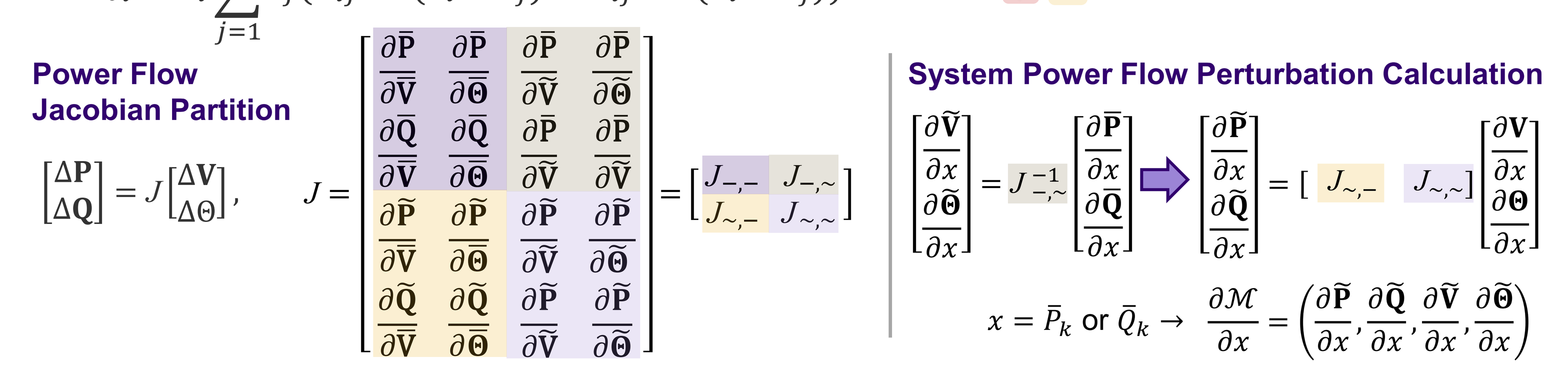
Power Flow Sensitivities

- **Perturbing the power injection at one bus perturbs other buses** resulting in a new operating point that satisfies the steady-state power flow equations

$$P_i = V_i \sum_{j=1}^{N} V_j \left(G_{kj}\cos(\theta_i - \theta_j) + B_{ij}\sin(\theta_i - \theta_j)\right),$$

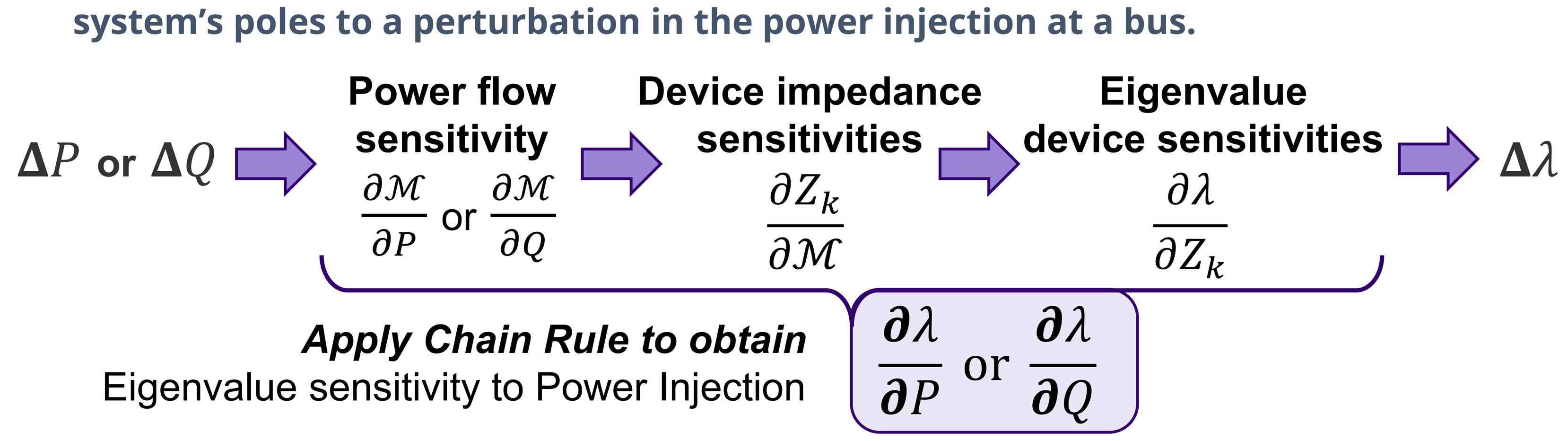
$$Q_i = V_i \sum_{j=1}^{N} V_j \left(G_{ij}\sin(\theta_i - \theta_j) - B_{ij}\,cos(\theta_i - \theta_j)\right).$$





Power Flow → Eigenvalue Sensitivity Indices

- **Changes in the power flow result in a change in equivalent device impedances** as we must re-linearize around the new operating point for each device in the system.
- Chaining first-order sensitivities together **we can calculate the sensitivity of the system's poles to a perturbation in the power injection at a bus.**



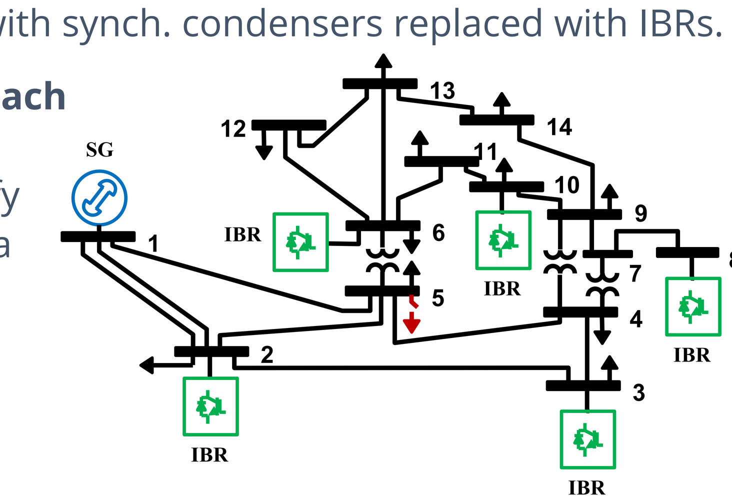
- Using these pole sensitivities to power injections **we define a modal power flow sensitivity index, and metrics relating to the maximum normalized pole shift towards the right-hand plane** for an increase or decrease in a power injection value at bus i as

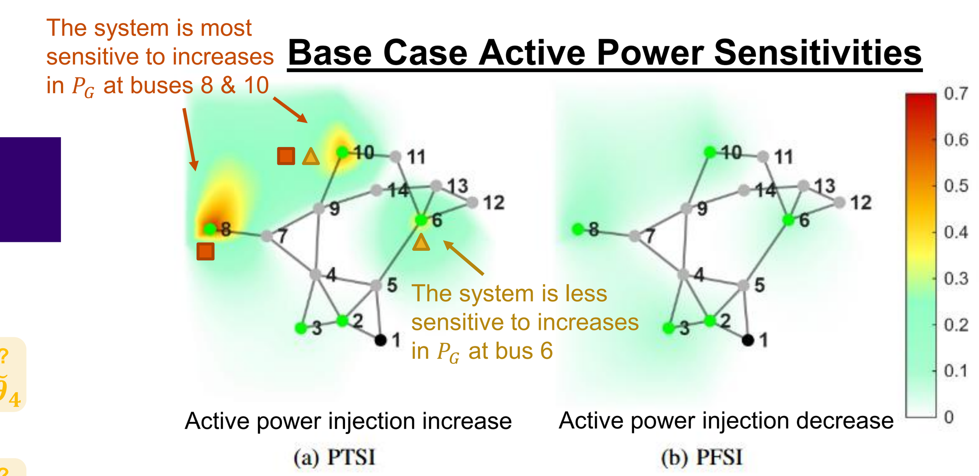
$$\boldsymbol{\mu}\mathbf{SI}_{i,\lambda} = \frac{\mathrm{re}(\Delta\lambda^{\mu_i})}{|\mathrm{re}(\lambda^{\mu_i})|},$$

$$\boldsymbol{\mu}\mathbf{TSI}_i = \max_{\lambda}\, \mu\mathrm{SI}_{i,\lambda}, \quad \boldsymbol{\mu}\mathbf{FSI}_i = \max_{\lambda}\, -\mu\mathrm{SI}_{i,\lambda}.$$

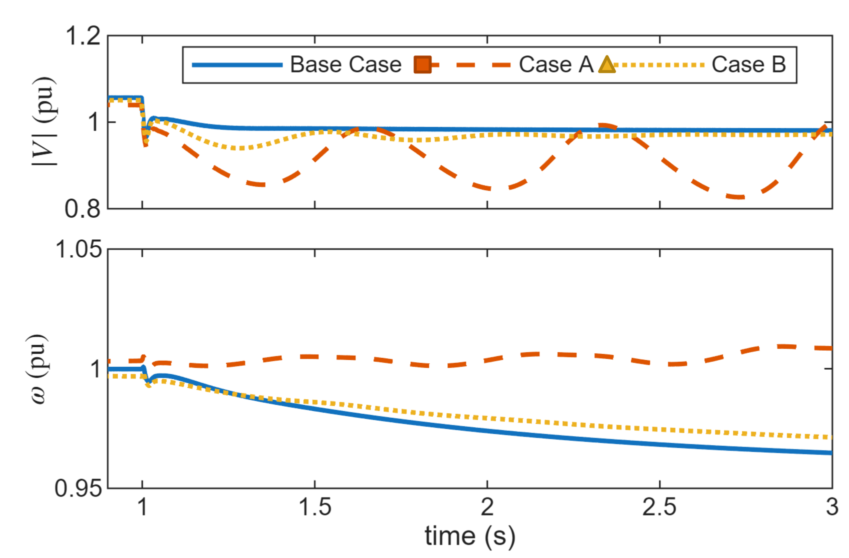
Case Study

- We test our approach with the IEEE 14-bus system with synch. condensers replaced with IBRs.
- Calculating **the power flow sensitivity indices at each bus identifies sensitive/weak buses.**
- We validate our proposed metrics' abilities to identify weak buses by simulating the system's response to a load step at bus 5 for various power injection cases.

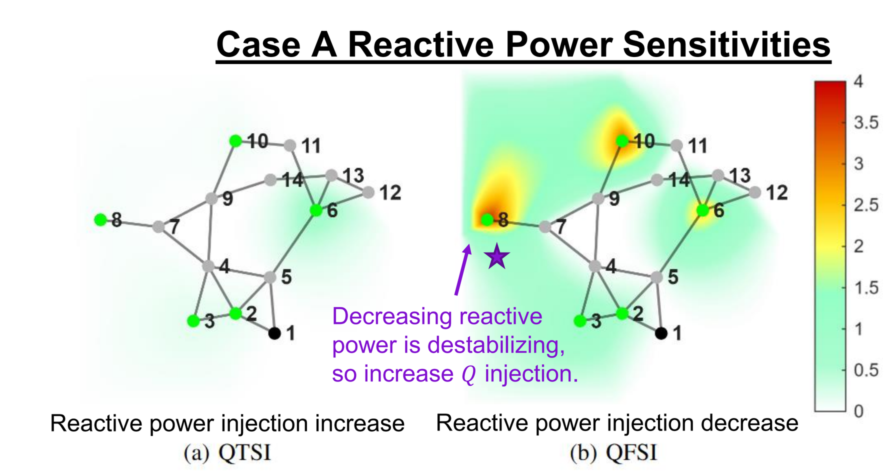


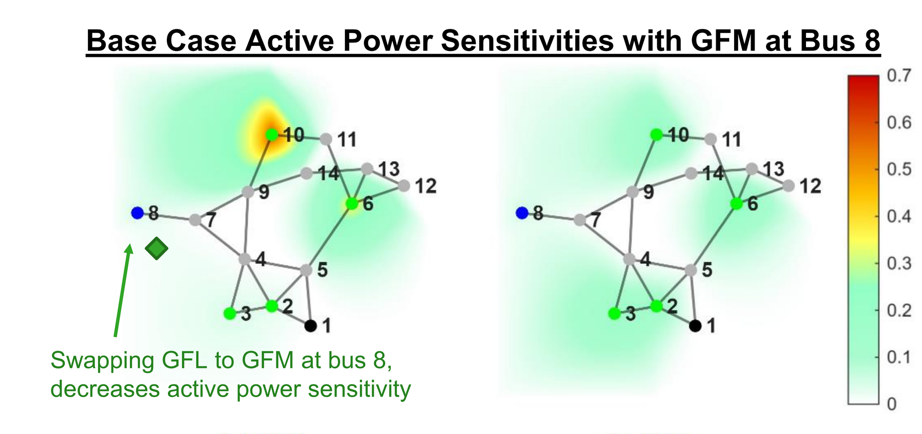


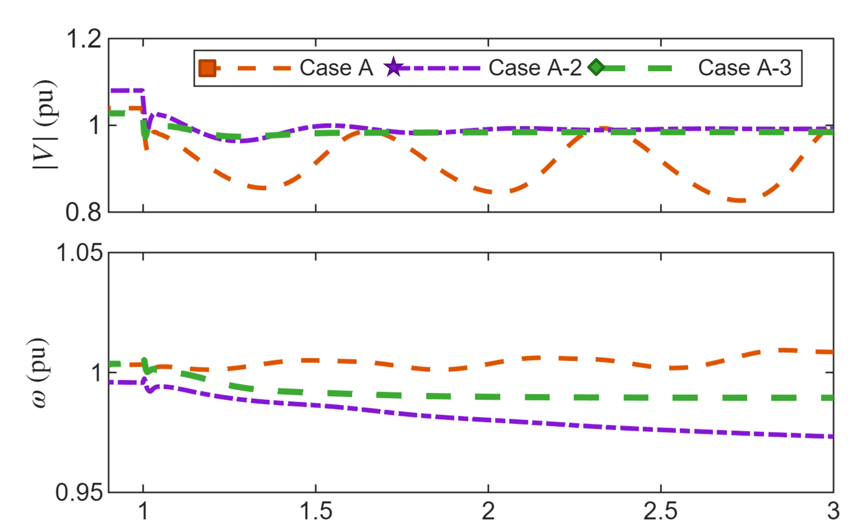
	Case	Changes from Base Case
■	Case A	PG : 0.5 pu → 1.2 pu at bus 8 and bus 10
▲	Case B	PG : 0.5 pu → 1.2 pu at bus 6 and bus 10
★	Case A-2	PG : 0.5 pu → 1.2 pu at bus 8 and bus 10, QG : 0.05 pu → 0.5 pu at bus 8.
◆	Case A-3	PG : 0.5 pu → 1.2 pu at bus 8 and bus 10, Bus 8 GFL to GFM control.



- These sensitivity indices can also be used to **identify remedial actions that system operators can take to improve stability.**







Future Work and References

- We will extend this work to consider sensitivities to changes in line admittance to **predict critical N-1 line outage cases, and dangerous or valuable line switching actions**.

[1] T. Joswig-Jones, S. Dong, J. Tan, D. Wu, and B. Zhang, "A review of system strength metrics for inverter-based power systems," 2026, accepted for publication at PES-GM 2026.
[2] Y. Gu, Y. Li, Y. Zhu, and T. C. Green, "Impedance-based whole-system modeling for a composite grid via embedding of frame dynamics," IEEE Trans. Power Syst., vol. 36, no. 1, p. 336–345, Jan. 2021.
[3] Y. Zhu, Y. Gu, Y. Li, and T. C. Green, "Participation analysis In impedance models: The grey-box approach for power system stability," IEEE Trans. Power Syst., vol. 37, no. 1, pp. 343–353, 2022.

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