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# Time-Domain Analysis of Power System Stability with Damping Control and Asymmetric Feedback Delays

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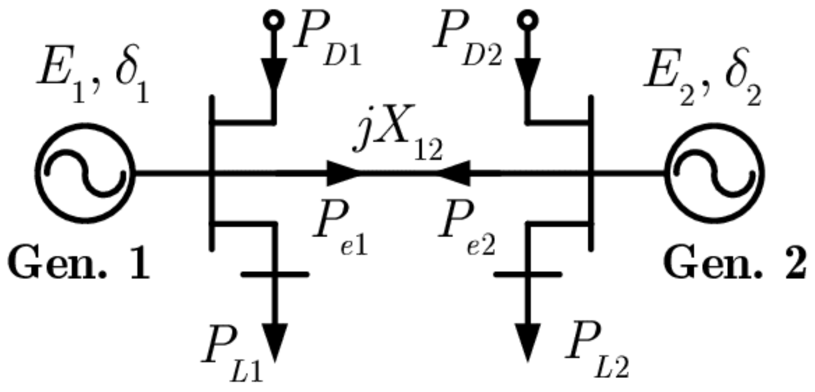
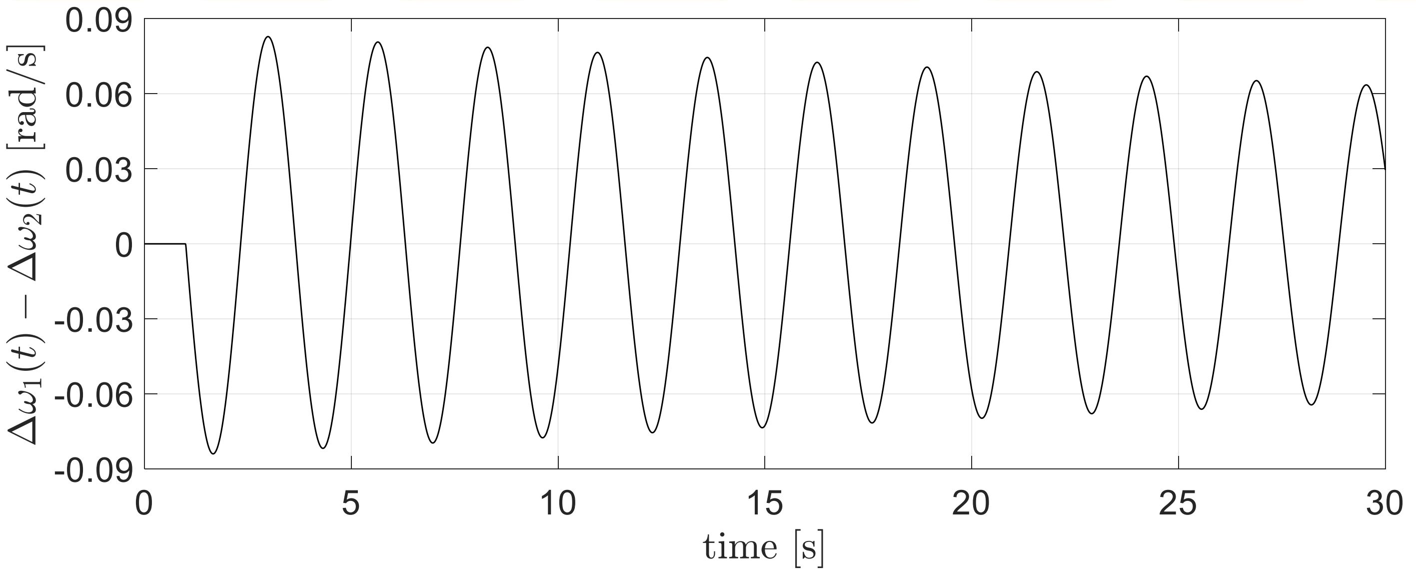
U.S. DEPARTMENT OF ENERGY

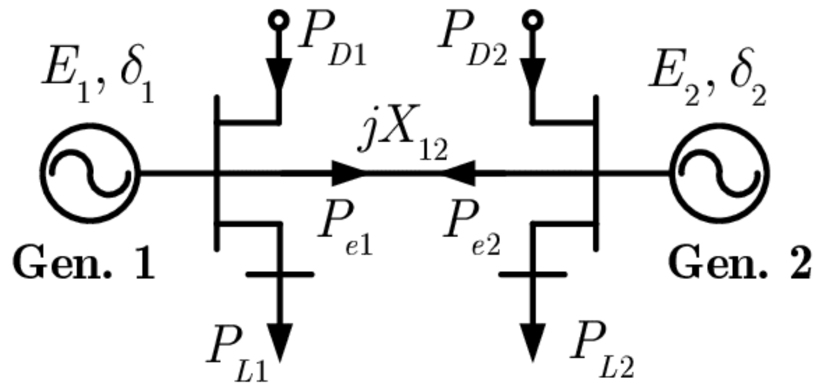
# Small Signal Stability




- Inter-area oscillations occur with change in load, fault in system, loss of generation
- Power injections can be used to for damping
- Wide-area measurements (e.g. from PMUs) can be used for feedback

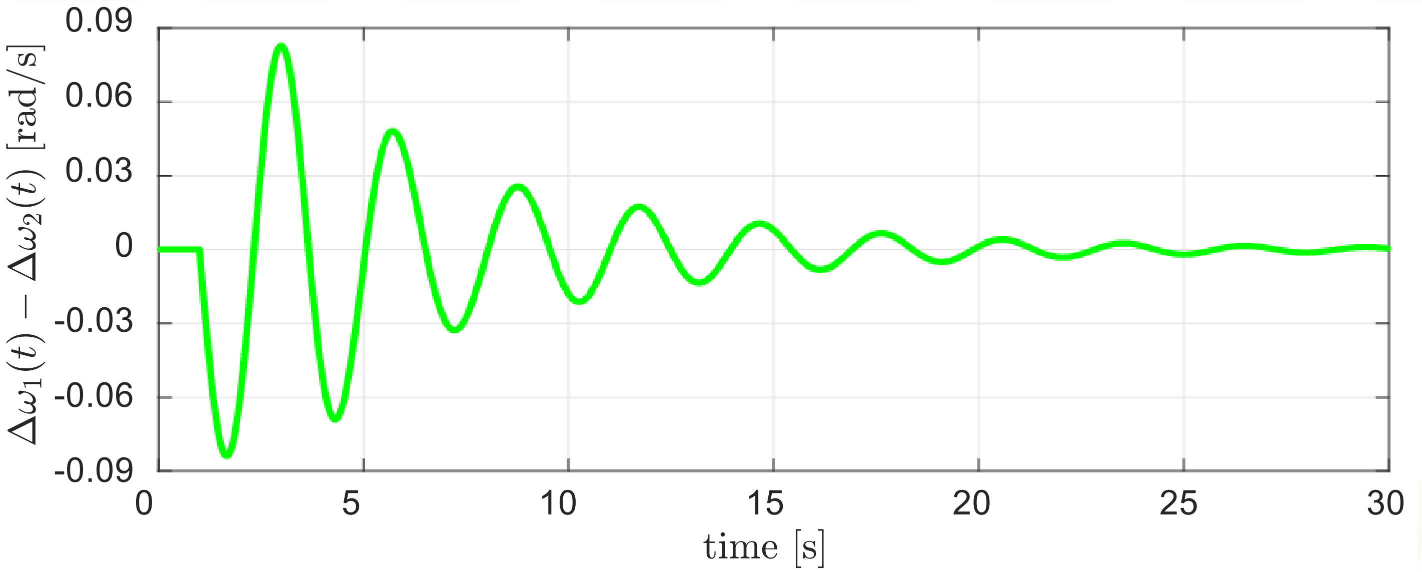


# Small Signal Stability

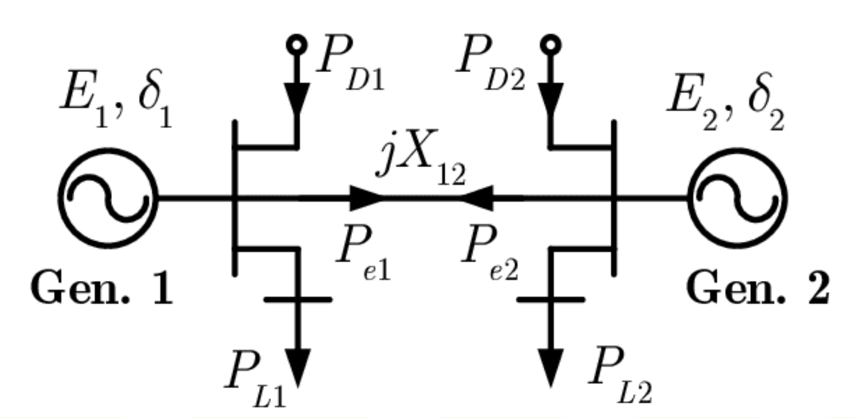



- Inter-area oscillations occur with change in load, fault in system, loss of generation
- Power injections can be used to for damping
- Wide-area measurements (e.g. from PMUs) can be used for feedback

Injections can come from
- HVDC line
- Energy storage devices



# Two-Area System Model




$$\dot{\delta}_i = \Omega \omega_i$$

$$2H_i \dot{\omega}_i = P_{mi} - P_{ei} - D_i \omega_i - \frac{1}{R_i}\omega_i - P_{Li} + P_{Di}$$

Electromechanical model

States:

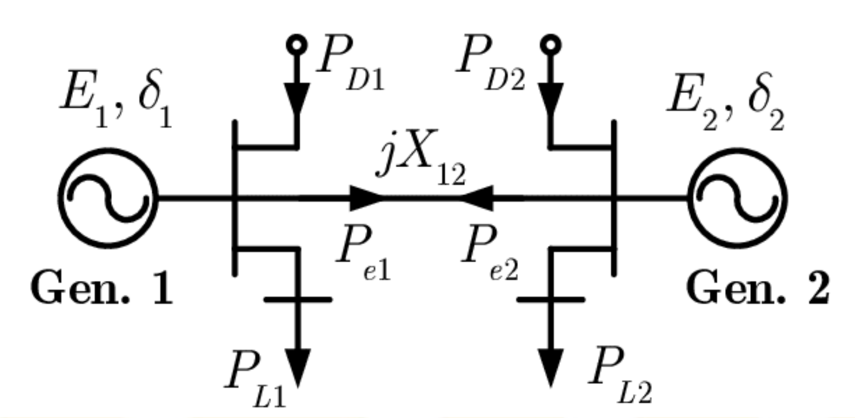
$\delta_i$ Generator rotor angle

$\omega_i$ Rotor angular velocity

$$P_{e1} = X_{12}^{-1} E_1 E_2 \sin(\delta_1 - \delta_2)$$

$$P_{e2} = X_{12}^{-1} E_2 E_1 \sin(\delta_2 - \delta_1)$$

# Two-Area System Model




$$\dot{\delta}_i = \Omega \omega_i$$

$$2H_i\dot{\omega}_i = P_{mi} - P_{ei} - D_i\omega_i - \frac{1}{R_i}\omega_i - P_{Li} + P_{Di}$$

- $H_i$: Inertia constant
- $P_{mi}$: Mechanical power input
- $P_{ei}$: Electrical power flow
- $D_i$: Damping coefficient
- $R_i$: Droop constant
- $P_{Li}$: Aggregated load
- $P_{Di}$: Controllable injection

States:

$\delta_i$ Generator rotor angle

$\omega_i$ Rotor angular velocity

$$P_{e1} = X_{12}^{-1} E_1 E_2 \sin(\delta_1 - \delta_2)$$

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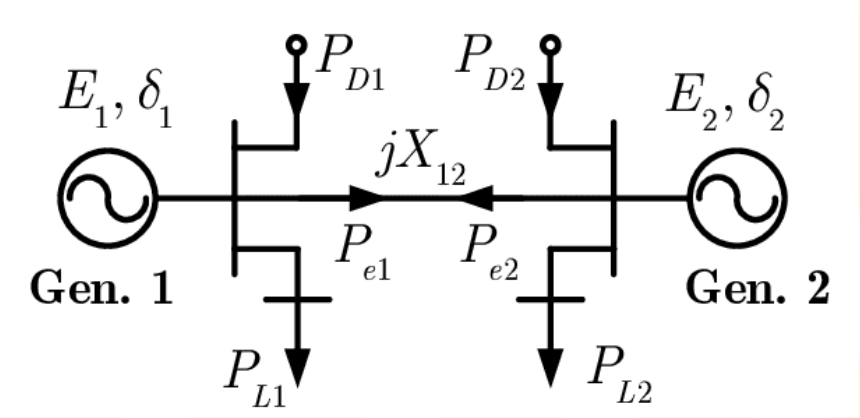
# Linearized System

$$\dot{\delta}_i = \Omega\omega_i$$

$$2H_i\dot{\omega}_i = P_{mi} - P_{ei} - D_i\omega_i - \frac{1}{R_i}\omega_i - P_{Li} + P_{Di}$$

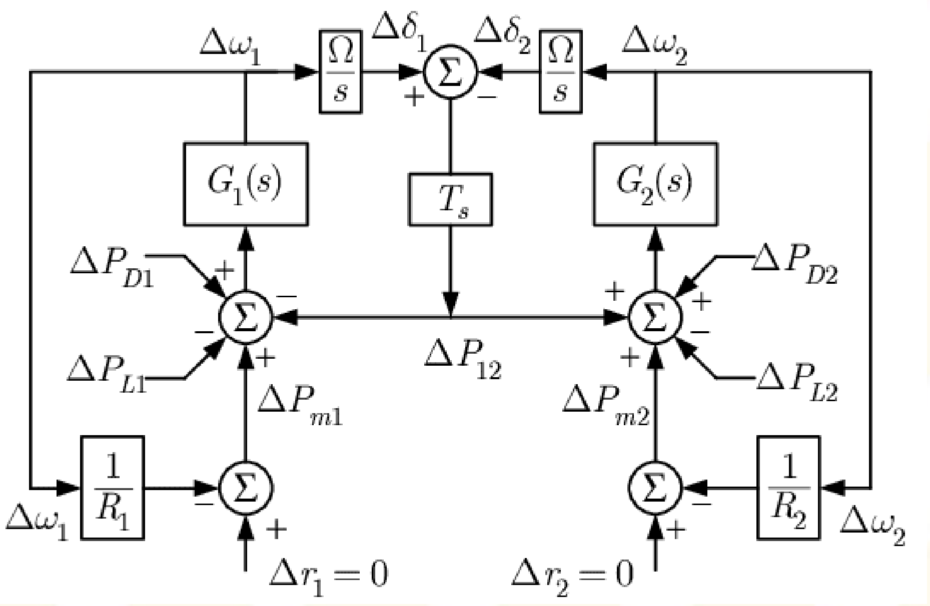



$$\dot{x}(t) = Ax(t) + B\Big(P_D(t) - P_L(t)\Big)$$

$$x(t) = \begin{bmatrix} \Delta\delta(t) \\ \Delta\omega(t) \end{bmatrix}$$

$$A = \begin{bmatrix} \mathbf{0} & \Omega I \\ -(2H)^{-1}T_s & -(2H)^{-1}(D + R^{-1}) \end{bmatrix}$$

$$B = \begin{bmatrix} \mathbf{0} \\ (2H)^{-1} \end{bmatrix}$$



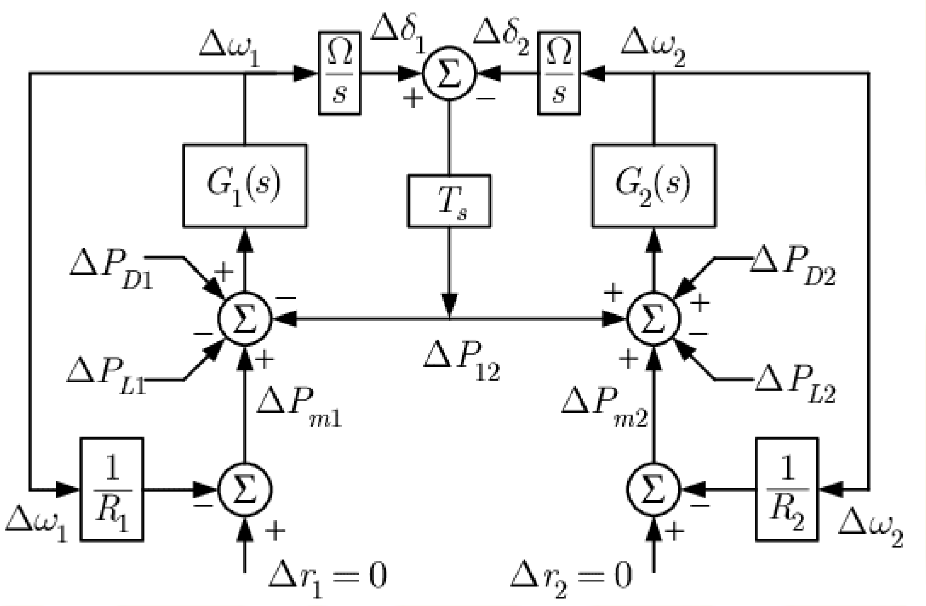

$$G_i(s) = \frac{1}{2H_i s + D_i}$$

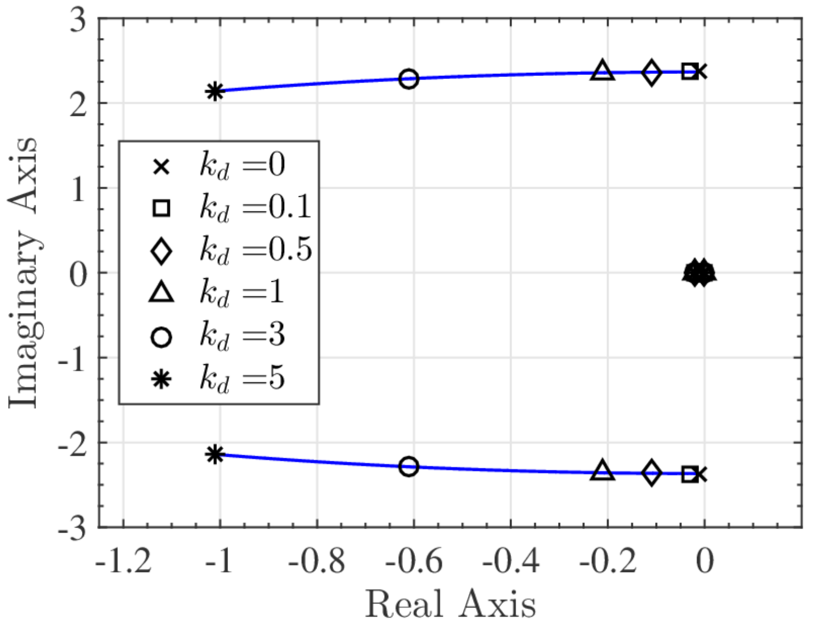
# Damping Controller

$$\dot{x}(t) = Ax(t) + B\Big(P_D(t) - P_L(t)\Big)$$

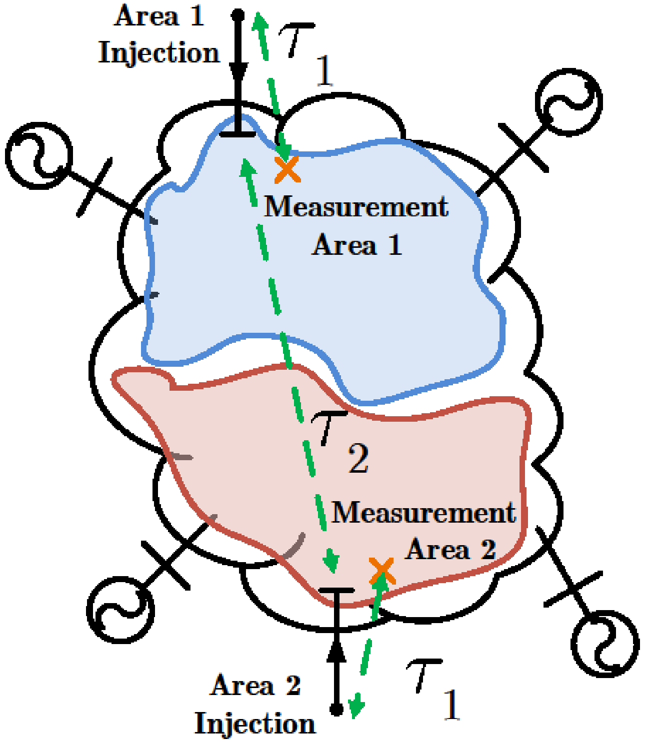
$$x(t) = \begin{bmatrix} \Delta\delta(t) \\ \Delta\omega(t) \end{bmatrix}$$

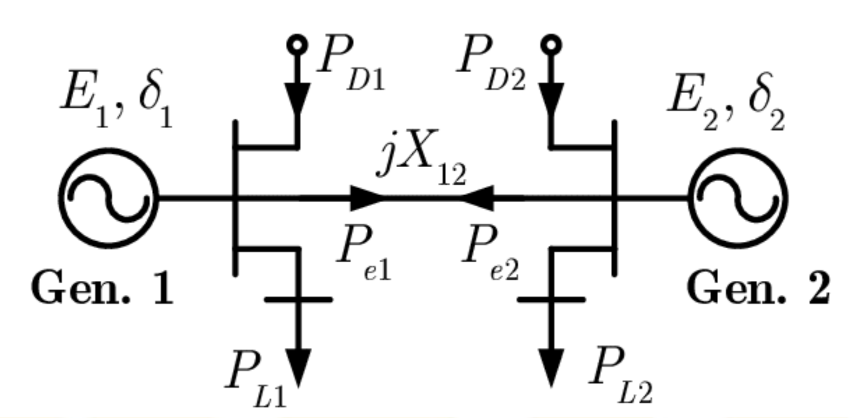
$$P_{D1}(t) = -k_d(\Delta\omega_1(t) - \Delta\omega_2(t))$$
$$P_{D2}(t) = -P_{D1}(t)$$





# Time-delay System

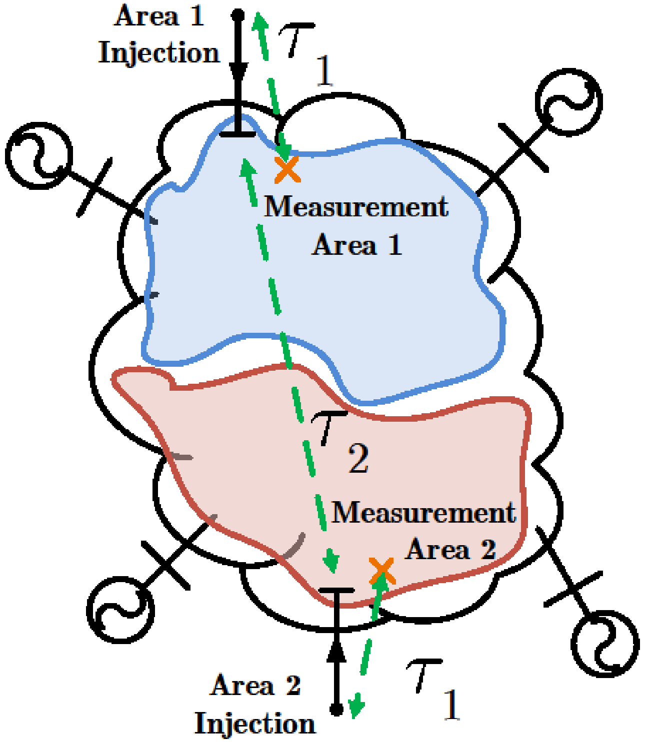


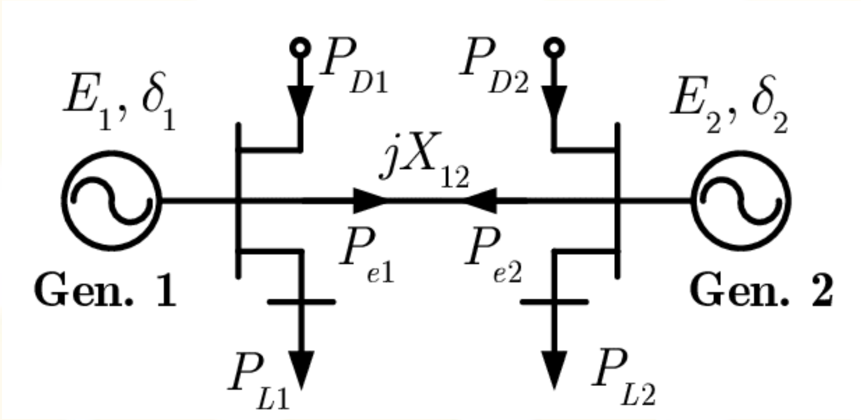




Time-delay system can be written as a Delay Differential Equation (DDE)

$$\dot{x}(t) = Ax(t) + A_1 x(t - \tau_1) + A_2 x(t - \tau_2)$$

# Time-delay System



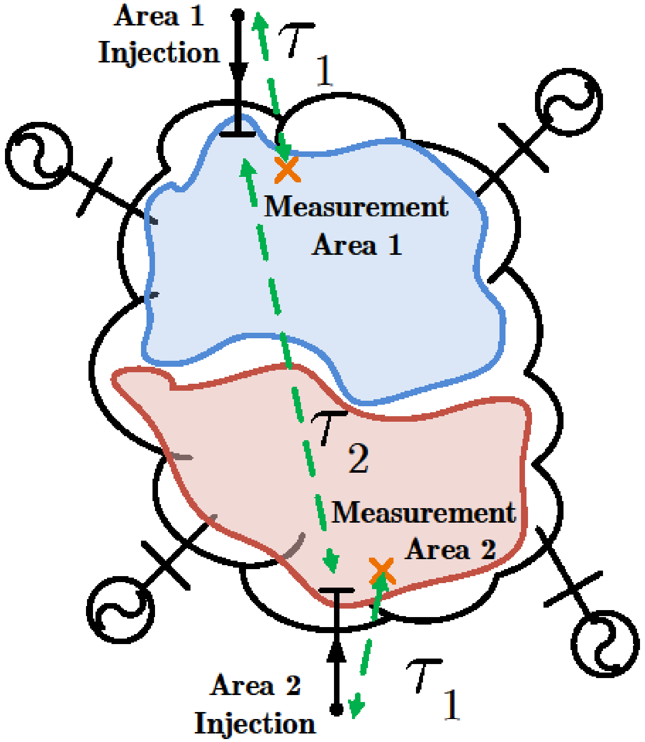




Time-delay system can be written as a Delay Differential Equation (DDE)

$$\dot{x}(t) = Ax(t) + A_1 x(t - \tau_1) + A_2 x(t - \tau_2)$$

- How much delay can the system handle?
- How does the distributed control action affect stability in the presence of delays?

# Damping Controller with Delays



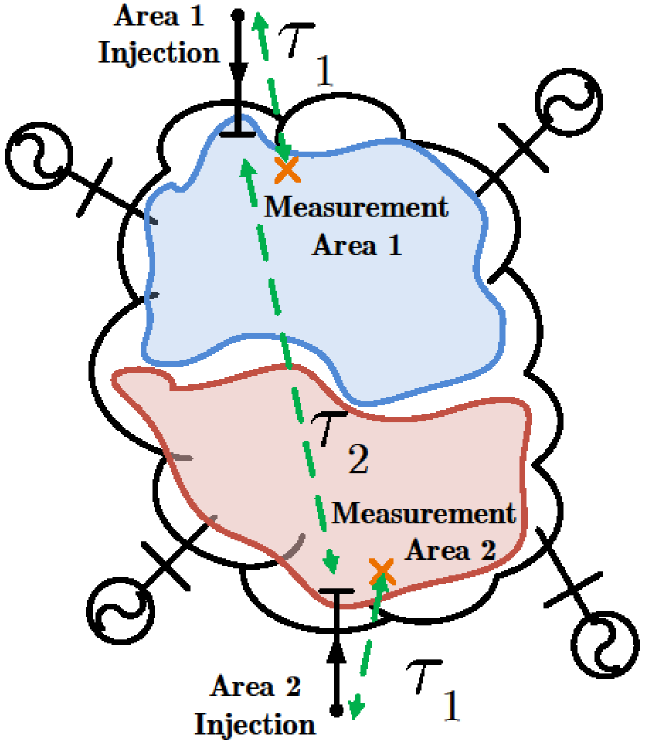

Damping control with HVDC:

$$P_{D1}(t) = -k_d(\Delta\omega_1(t-\tau_1) - \Delta\omega_2(t-\tau_2))$$
$$P_{D2}(t) = k_d(\Delta\omega_1(t-\tau_1) - \Delta\omega_2(t-\tau_2))$$

Damping control with ES:

$$P_{D1}(t) = -k_d(\Delta\omega_1(t-\tau_1) - \Delta\omega_2(t-\tau_2))$$
$$P_{D2}(t) = k_d(\Delta\omega_1(t-\tau_2) - \Delta\omega_2(t-\tau_1))$$

# Closed-loop Dynamics with Delay




$$\dot{x}(t) = Ax(t) + A_1x(t-\tau_1) + A_2x(t-\tau_2) + B_LP_L(t)$$

**HVDC:**

$$A_1^{HV} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{-k_d}{2H_1} & 0 \\ 0 & 0 & \frac{k_d}{2H_2} & 0 \end{bmatrix}$$

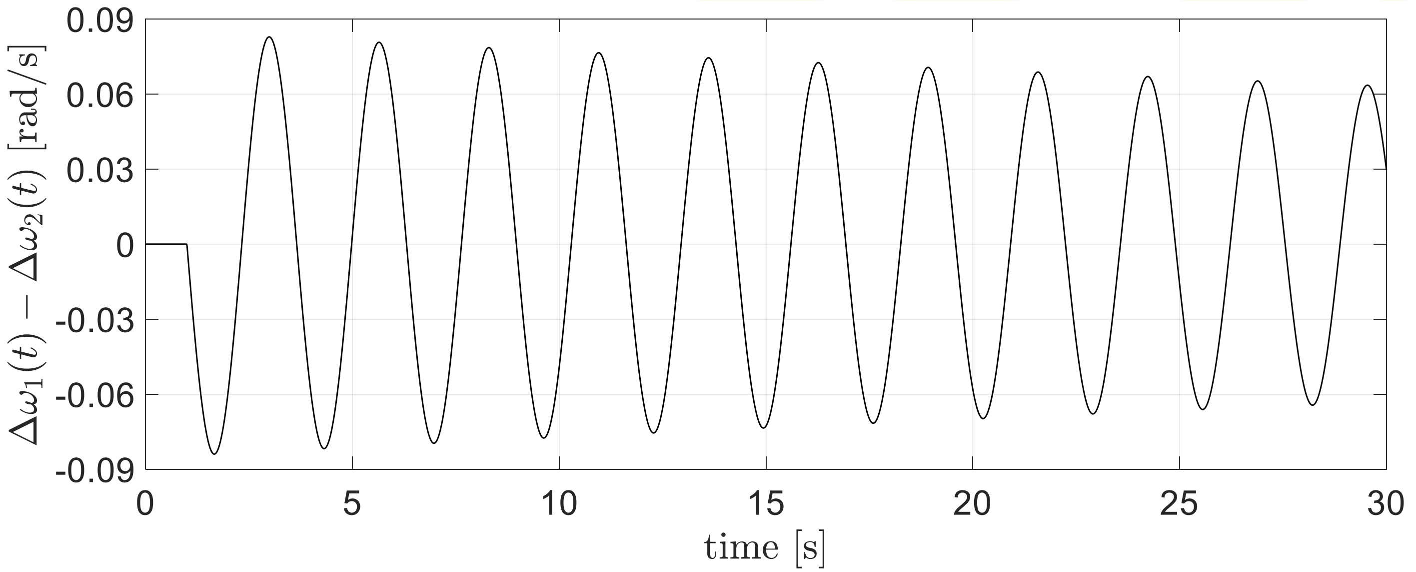
$$A_2^{HV} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{k_d}{2H_1} \\ 0 & 0 & 0 & \frac{-k_d}{2H_2} \end{bmatrix}$$

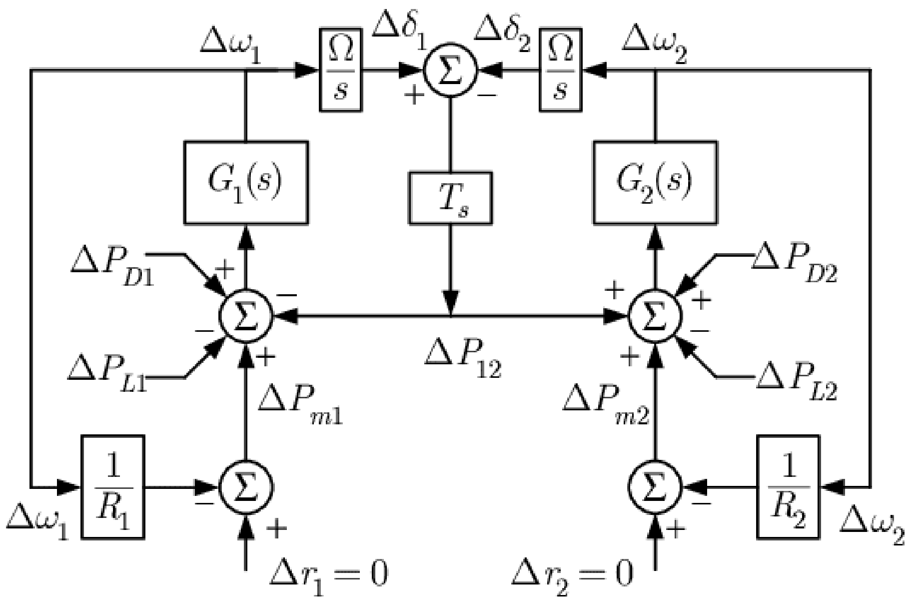
**ES:**

$$A_1^{ES} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{-k_d}{2H_1} & 0 \\ 0 & 0 & 0 & \frac{-k_d}{2H_2} \end{bmatrix}$$

$$A_2^{ES} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{k_d}{2H_1} \\ 0 & 0 & \frac{k_d}{2H_2} & 0 \end{bmatrix}$$

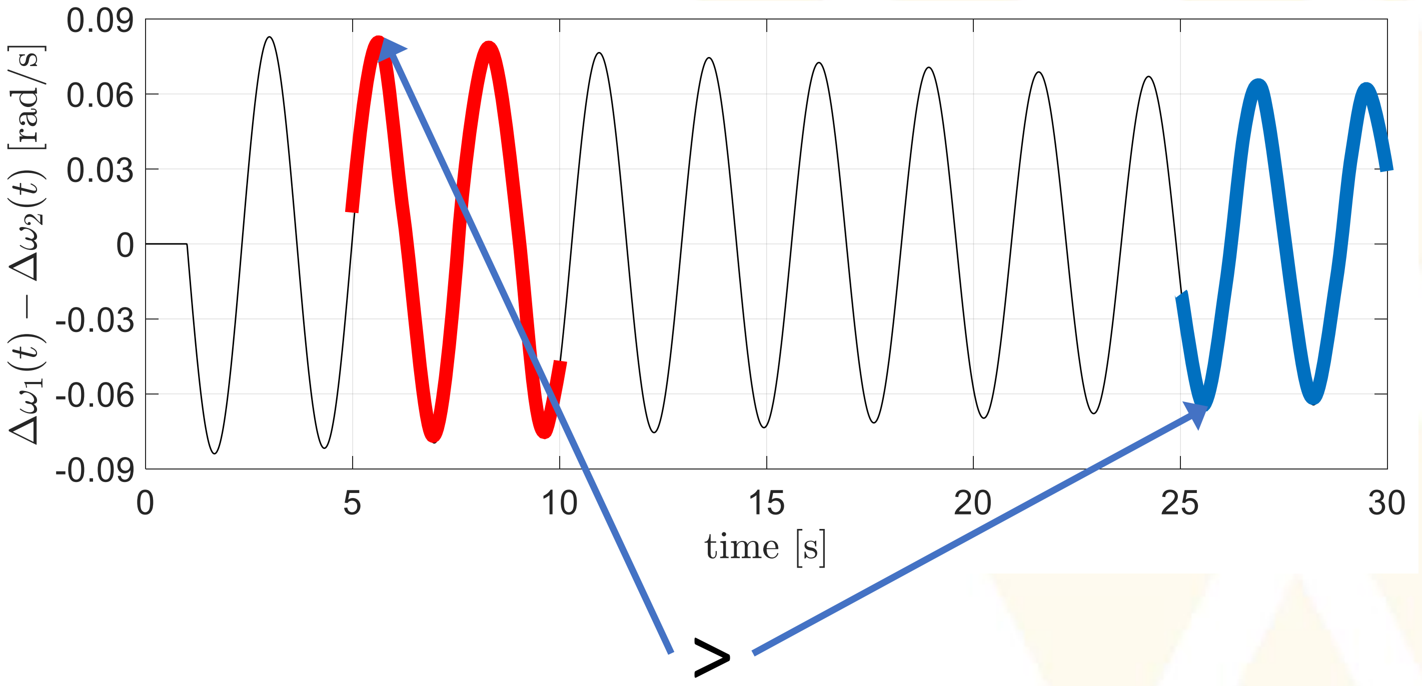
# Stability Criterion

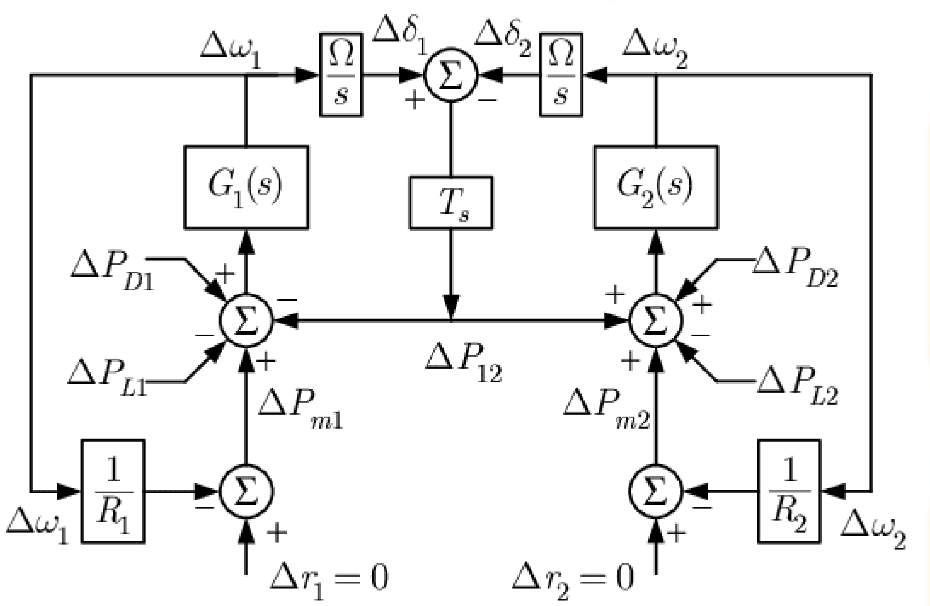



Natural system response after sudden change in load.

# Stability Criterion




Largest amplitude in red > largest amplitude in blue ➡ stable

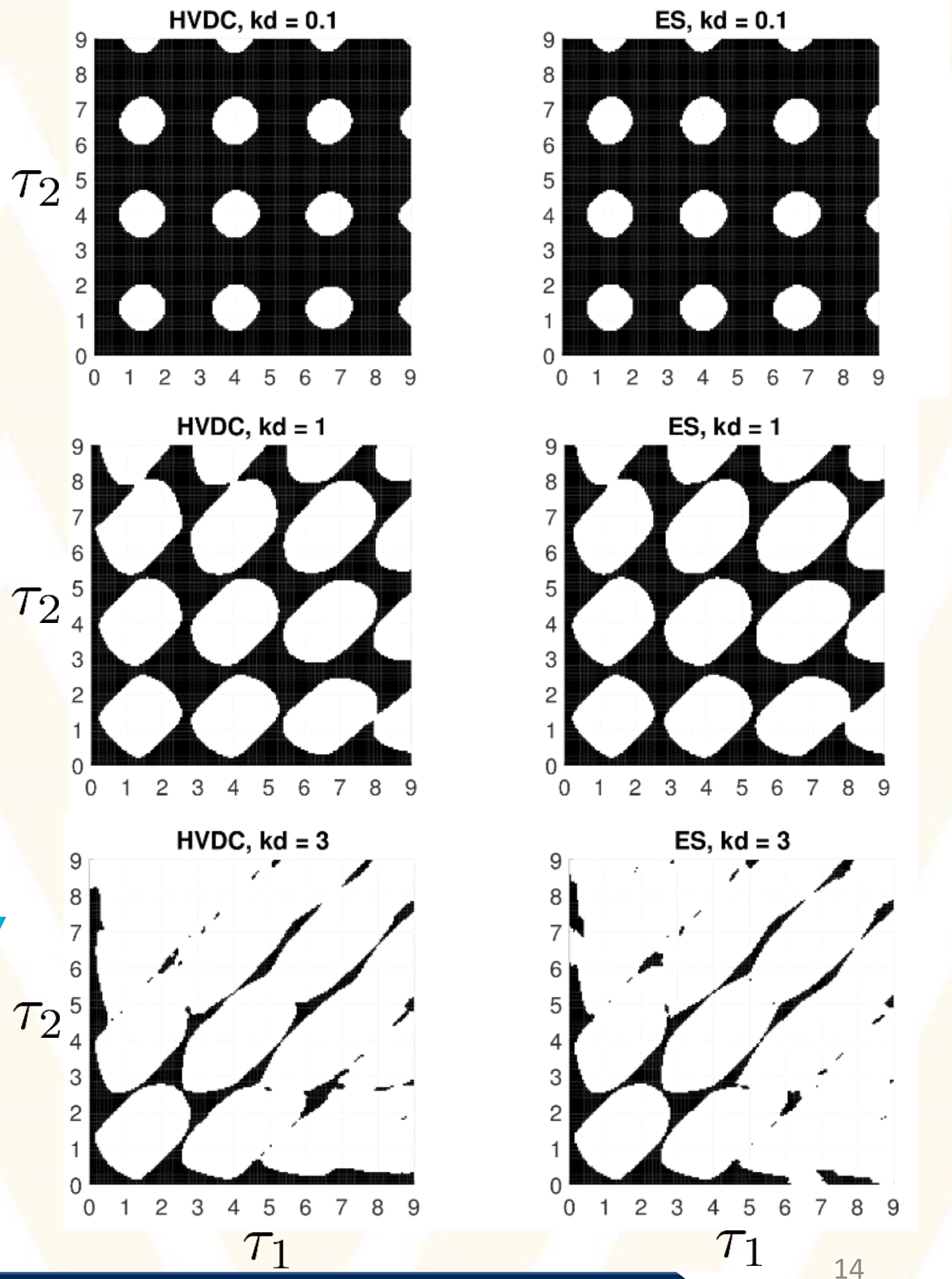
Using this criterion, determine regions of stability that depend on time delays $\tau_1, \tau_2$ and damping gain $k_d$.

# Stability Regions

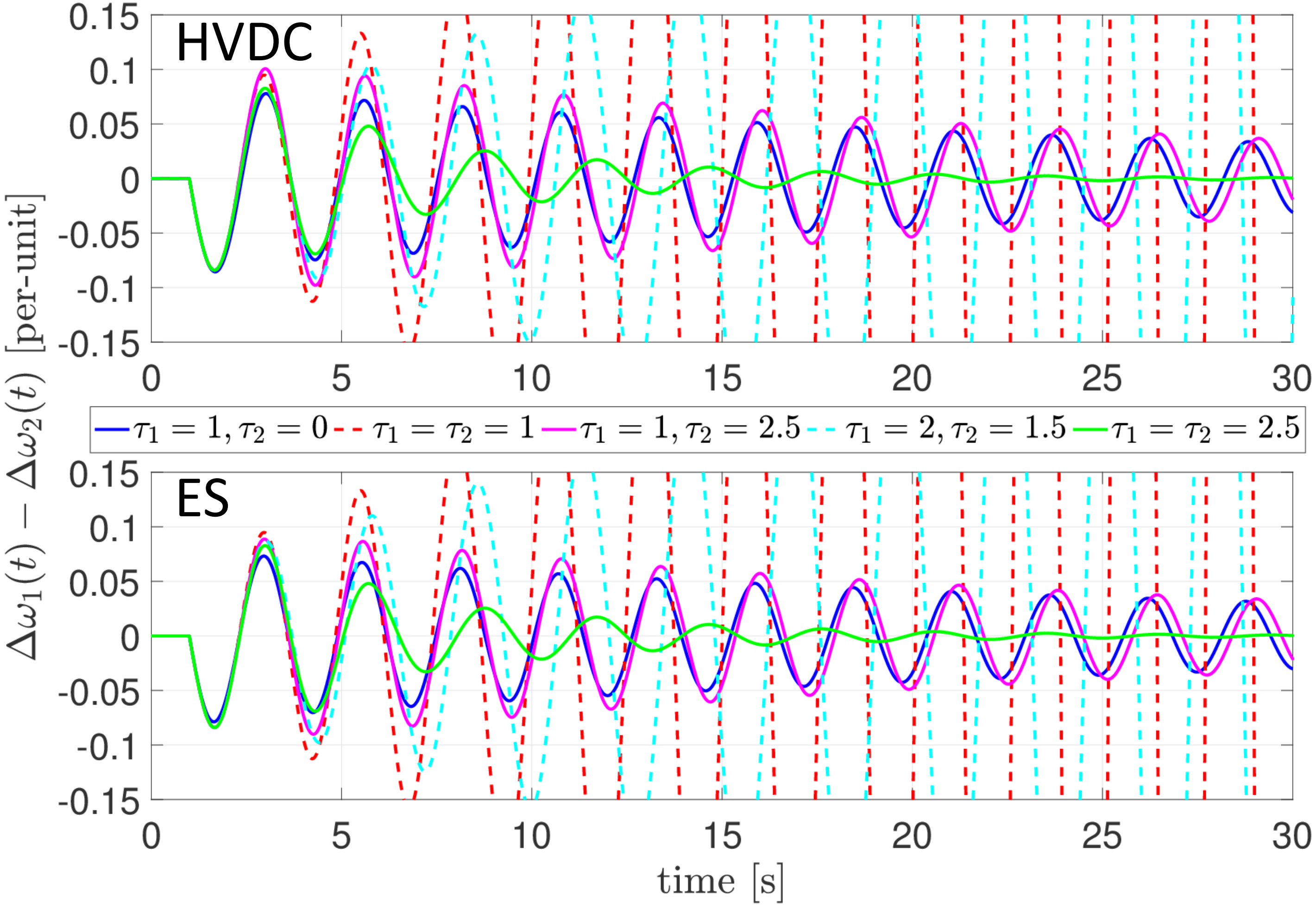
Black: Stable

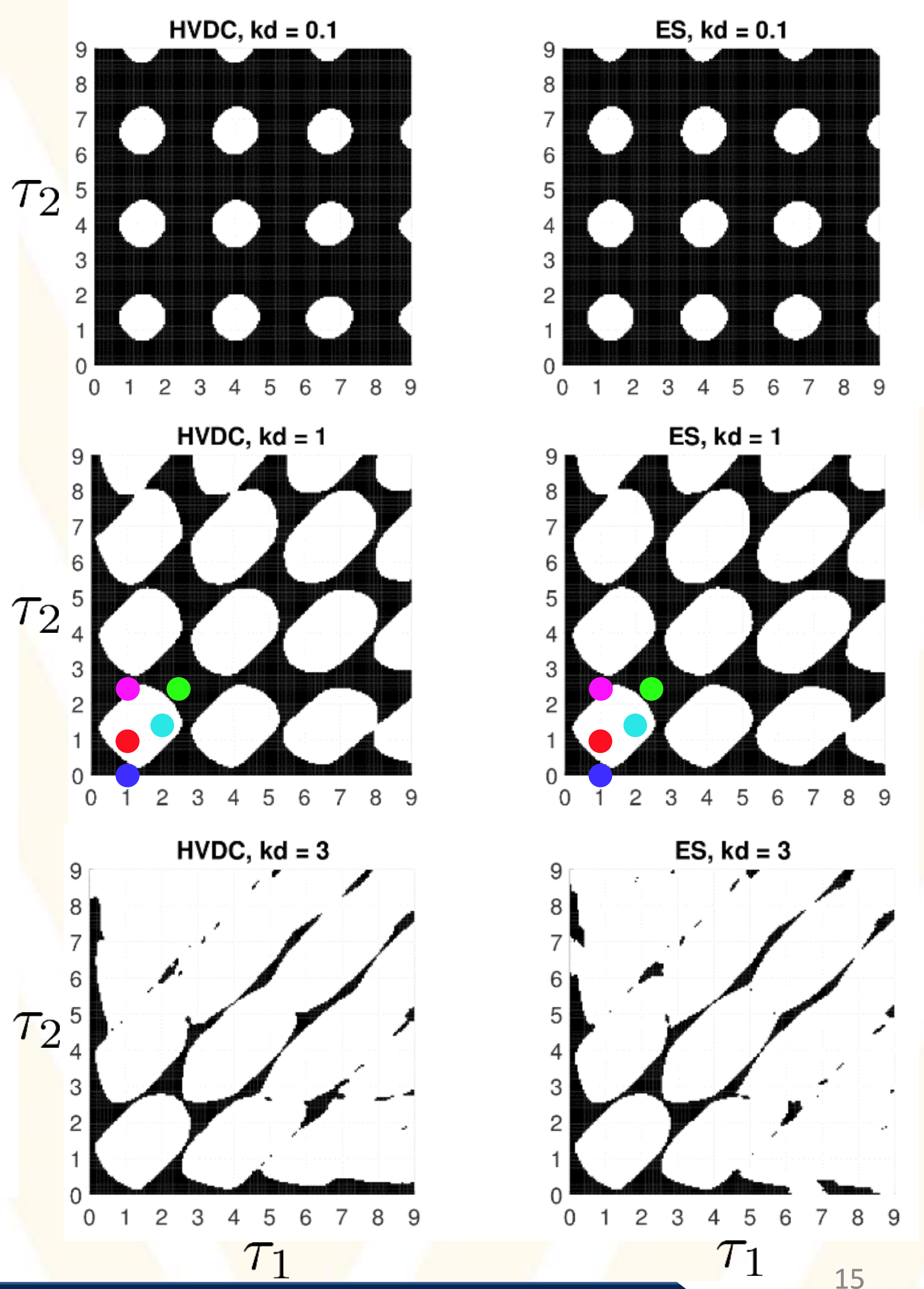
White: Unstable

In the presence of delays, increasing damping may lead to instability.

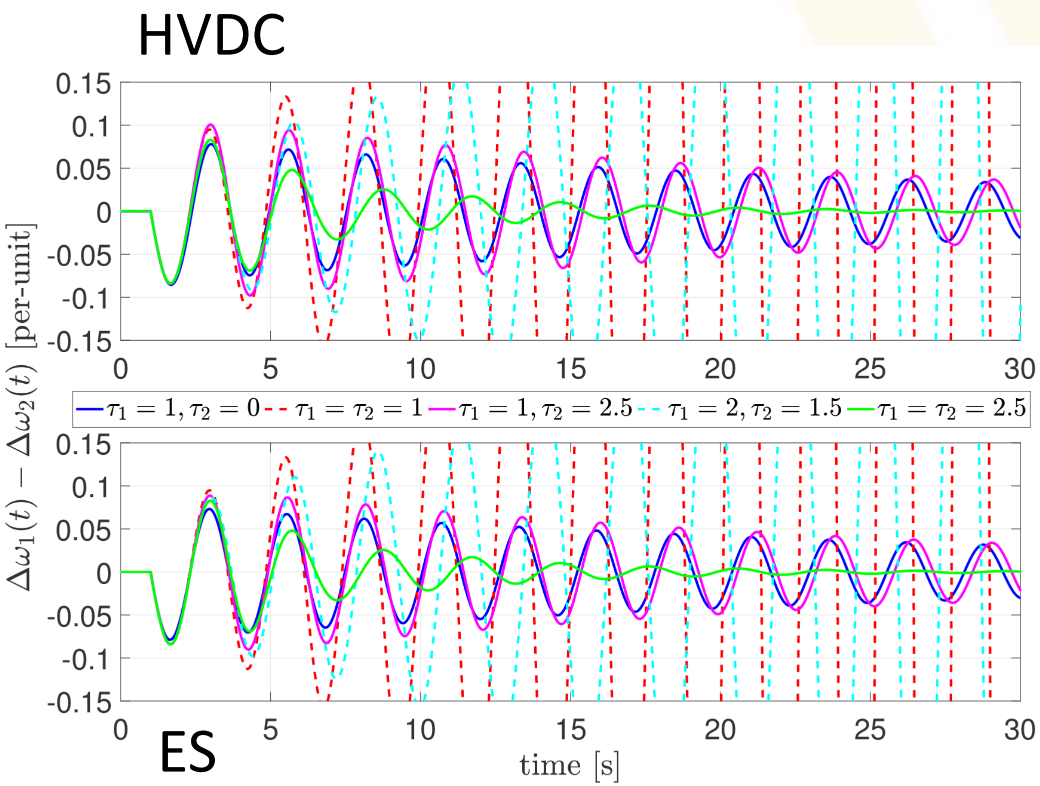


# Time Simulations

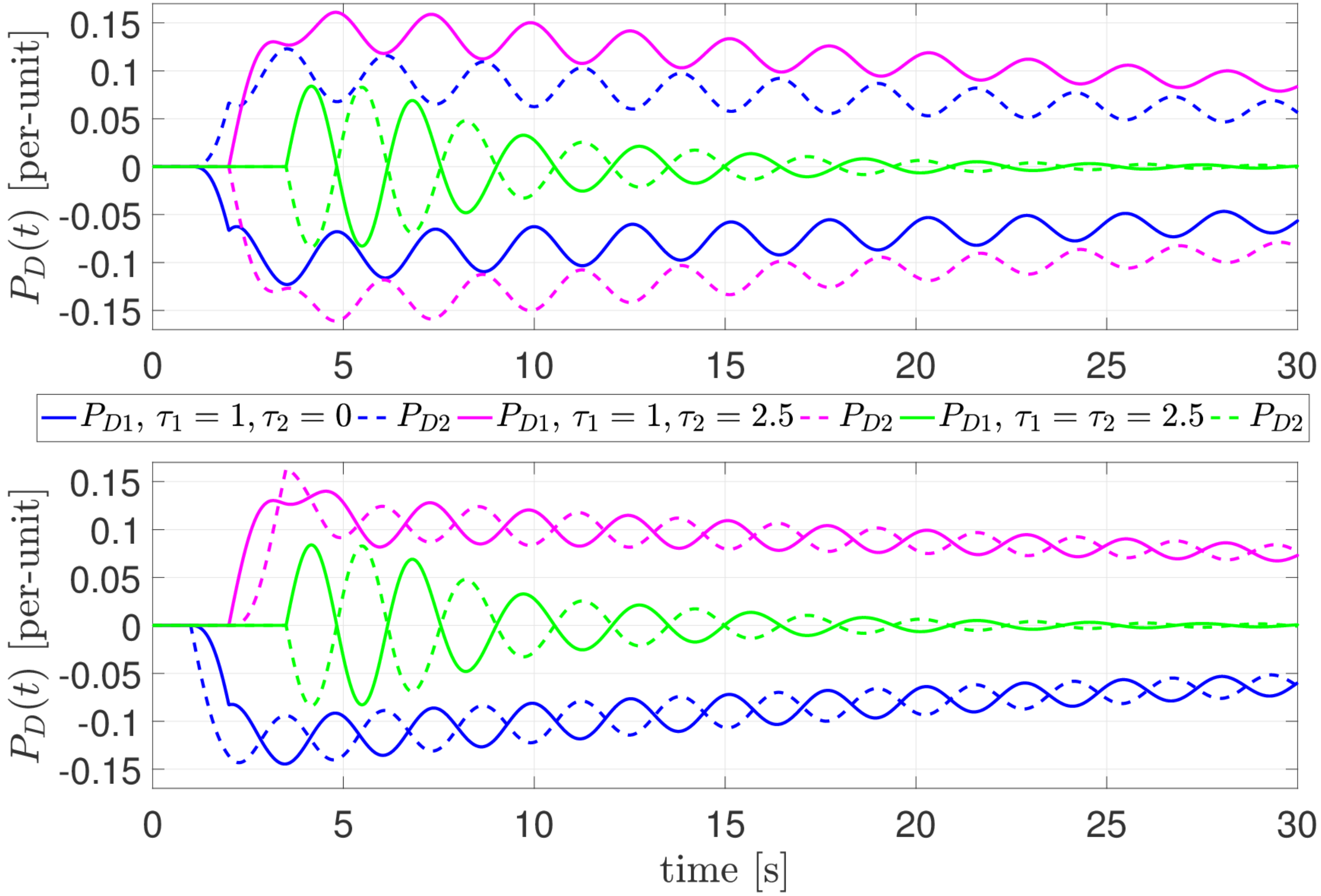


# Time Simulations



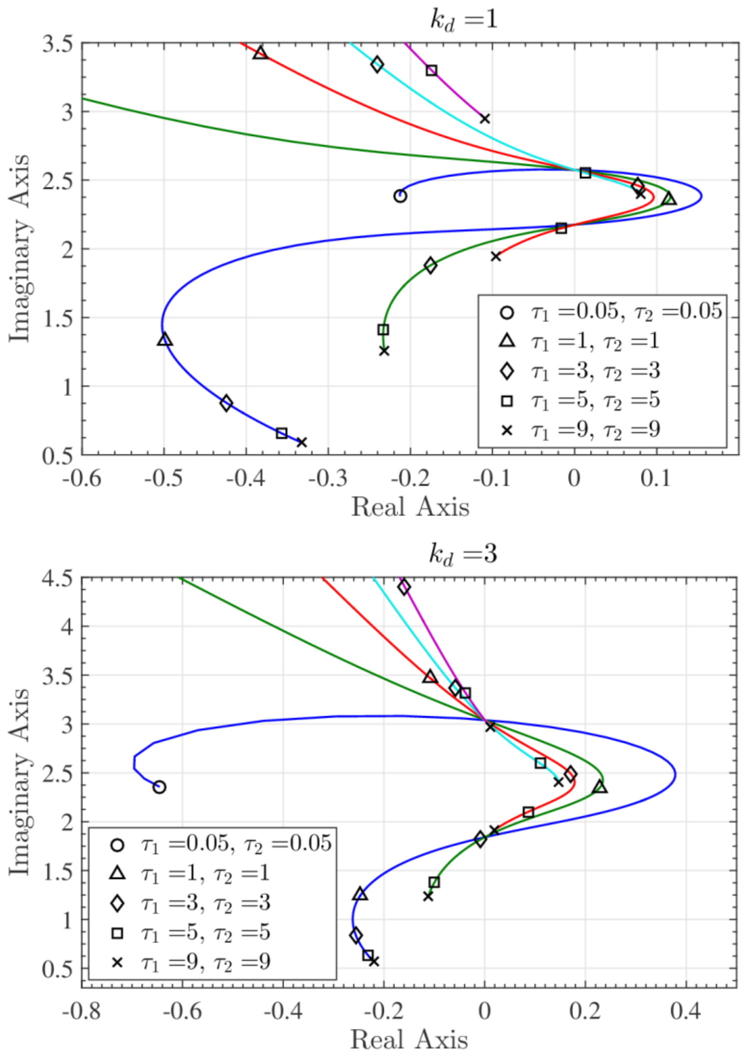

# Injections



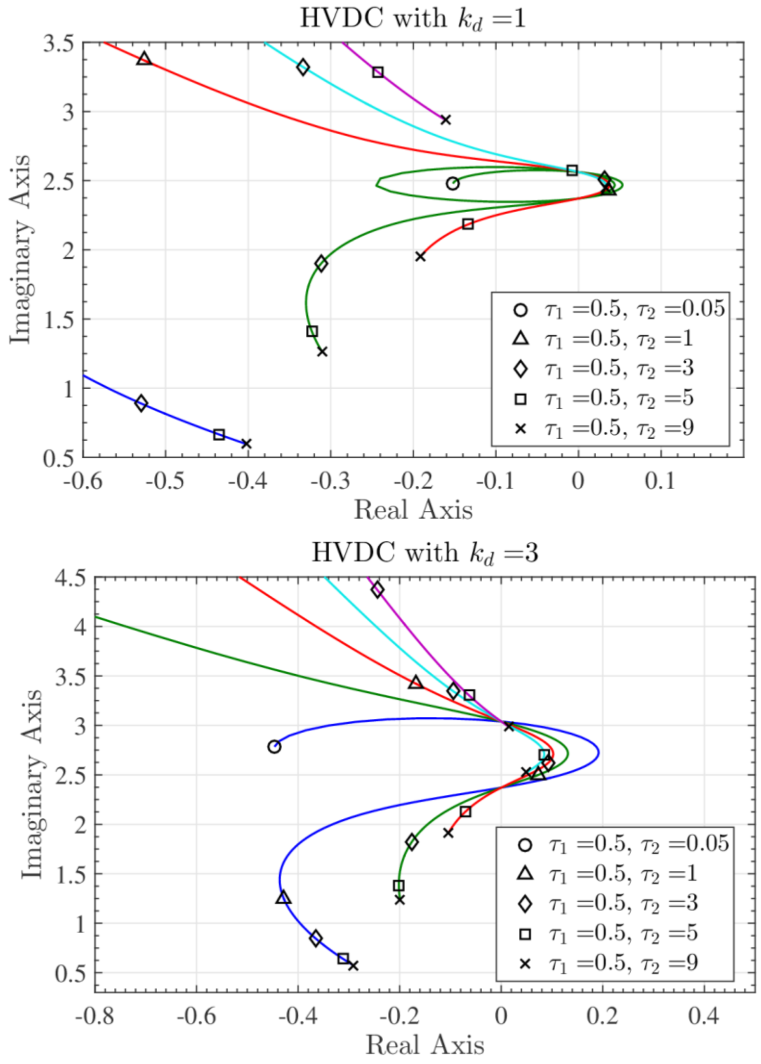
# Eigenvalues

## Asymmetric Delays:

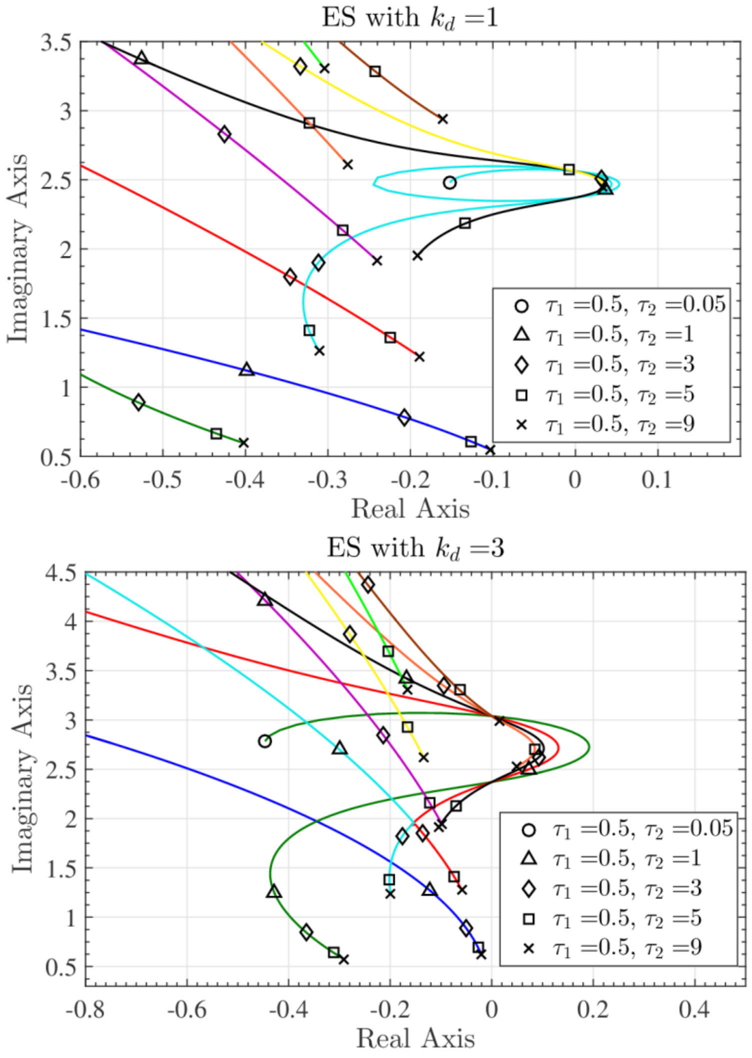
## Equal Delays:




## HVDC:




## ES:



# Conclusions

- Wide-area damping control can be used to damp inter-area oscillations.
- Time delays in the feedback signals can cause the damping control to destabilize the system.
- Stability depends on the size of the time delays as well as the size of the damping control gain.
- Increasing the delay (e.g. to better match the period of oscillation) can have a stabilizing effect.

# Acknowledgements


- Funding provided by US DOE Energy Storage Program managed by Dr. Imre Gyuk of the DOE Office of Electricity Delivery and Energy Reliability.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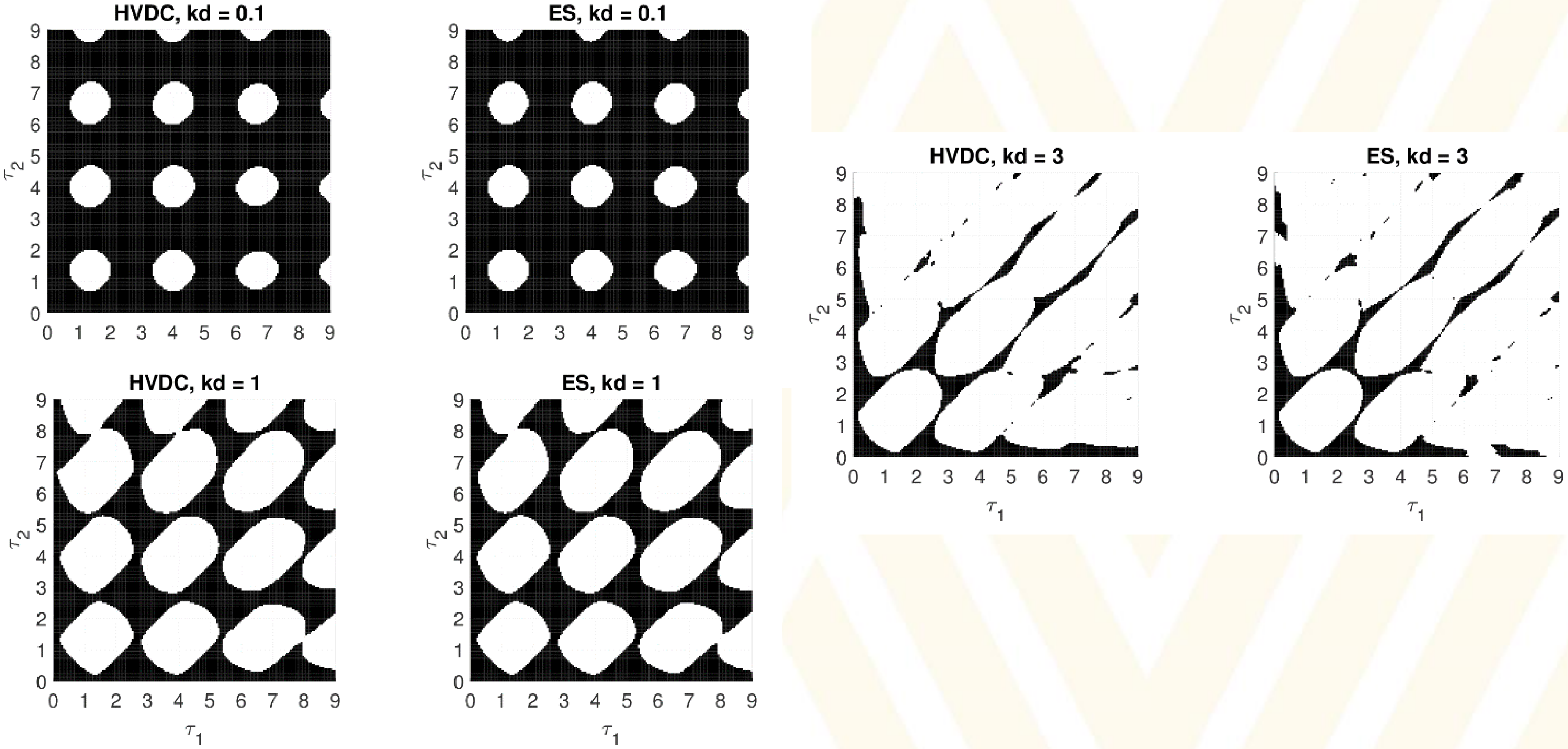
Thank you.

# Extra Slides

# Stability Regions



# Parameters

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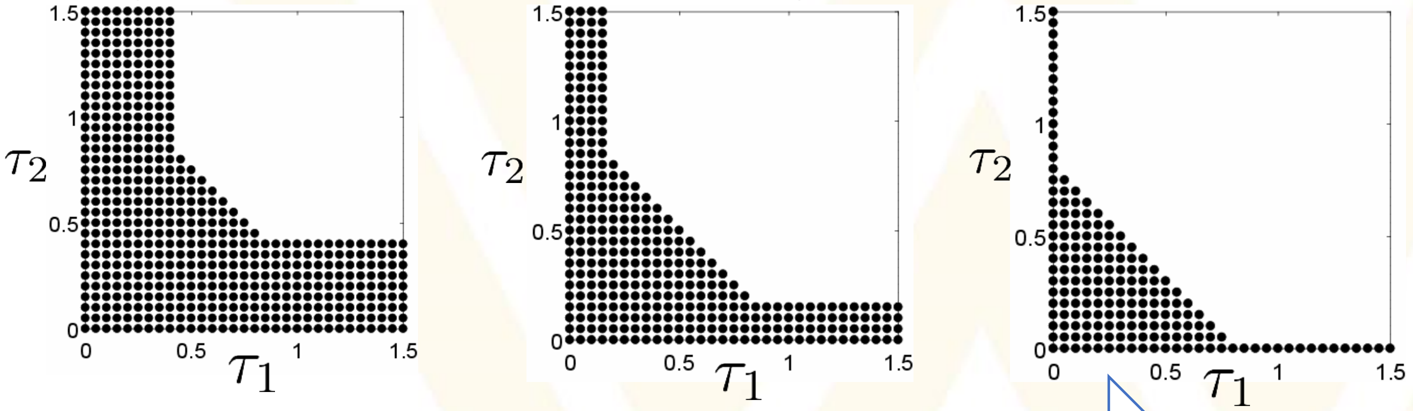
$$2H_i \dot{\omega}_i = P_{mi} - P_{ei} - D_i \omega_i - \frac{1}{R_i}\omega_i - P_{Li} + P_{Di}$$

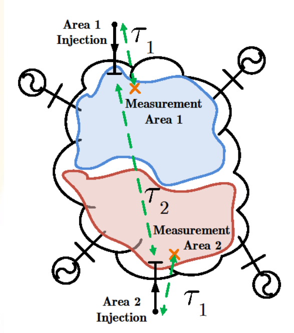
$$\dot{x}(t) = Ax(t) + B\Big(P_D(t) - P_L(t)\Big)$$

$$A = \begin{bmatrix} \mathbf{0} & \Omega I \\ -(2H)^{-1}T_s & -(2H)^{-1}(D + R^{-1}) \end{bmatrix}$$

| $D_1 + R_1^{-1}$ | $D_2 + R_2^{-1}$ | $H_1$ | $H_2$ | $T_s$ |
|---|---|---|---|---|
| 0.1 | 0.1 | 2.5 | 2.5 | 14 |

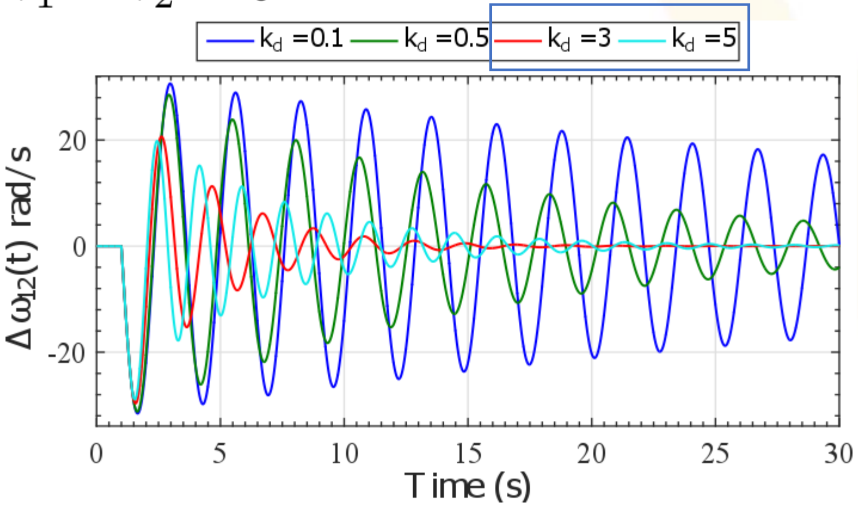
# Time Delays and Instability



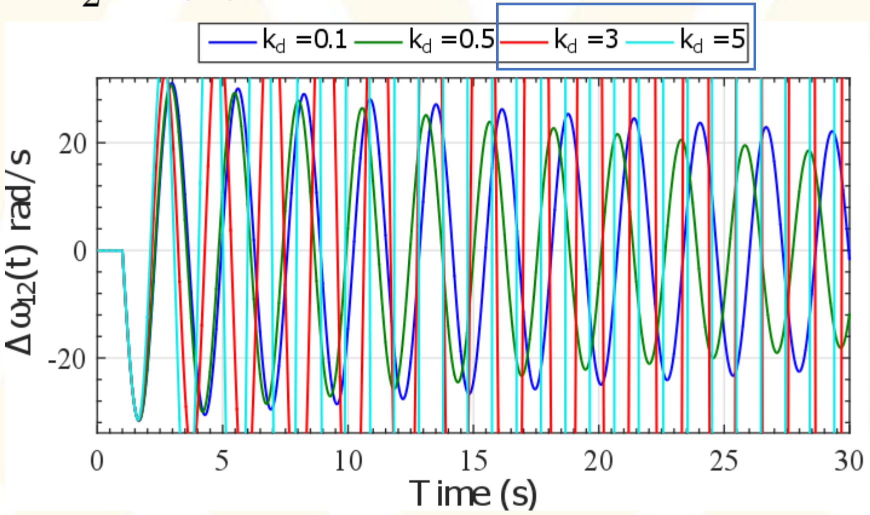




Increasing damping

$\tau_1 = \tau_2 = 0.4$




$\tau_1 = \tau_2 = 0.6$




- In the presence of time delays, increasing damping may lead to instability.