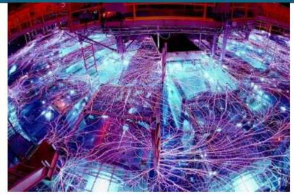
SAND2020-5977C

Sandia National Laboratories

A Frequency-shaped Controller for Damping Inter-area Oscillations in Power Systems



PRESENTED BY

Felipe Wilches-Bernal, David A. Schoenwald, Brian J. Pierre, and Raymond H. Byrne

Electric Power Systems Research Department
Sandia National Laboratories
Albuquerque, NM

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Presentation Outline

- Context and Introduction
- Frequency Shaping Optimal Control
- Controller Design
- Results in a test power system
- Conclusions

Context and Introduction

- Wide-area measurements in power systems make possible to study global control approaches.

- Inter-area oscillations are a phenomenon that affect sparsely interconnected power systems and occur at a narrow and defined frequency range (0.1 – 1Hz). This phenomenon is global (affects the entire interconnection) and can be addressed with wide-area control

- An approach that focuses the control action to a defined frequency range is appropriate for this problem

- Such an approach is frequency shaping optimal control

Frequency Shaping Optimal Control

- For a linear time invariant system described by

$$\dot{x}(t) = Ax(t) + Bu(t)$$
$$y(t) = Cx(t)$$

$x \in \mathbb{R}^n$ states $u \in \mathbb{R}^m$ control inputs $y \in \mathbb{R}^p$ outputs

- The standard optimal control approach aims at finding the optimal input $u(t)$ to minimize the cost function

$$J(u) = \int_0^\infty \left(x(t)^\top Q x(t) + u(t)^\top R u(t)\right) dt \quad \text{where} \quad Q \geq 0 \in \mathbb{R}^{n\times n} \quad R > 0 \in \mathbb{R}^{m\times m}$$

Time domain

- Using Parseval's theorem

$$J(u) = \frac{1}{2\pi} \int_0^\infty \left(X(j\omega)^{\mathsf{H}} Q X(j\omega) + U(j\omega)^{\mathsf{H}} R U(j\omega)\right) d\omega$$

Frequency domain

Frequency Shaping Optimal Control

- Working in the frequency domain, the state and input cost (Q, R) matrices can be made frequency dependent as

$$
\begin{aligned}
Q(j\omega) &= Q_{\mathrm{f}}(j\omega)^{\mathsf{H}} Q_{\mathrm{f}}(j\omega) \succeq 0 \\
R(j\omega) &= R_{\mathrm{g}}(j\omega)^{\mathsf{H}} R_{\mathrm{g}}(j\omega) \succ 0
\end{aligned}
$$

- The state and the input can also be redefined as

$$
\begin{aligned}
X_{\mathrm{f}}(j\omega) &= Q_{\mathrm{f}}(j\omega) X(j\omega) \\
U_{\mathrm{g}}(j\omega) &= R_{\mathrm{g}}(j\omega) U(j\omega)
\end{aligned}
$$

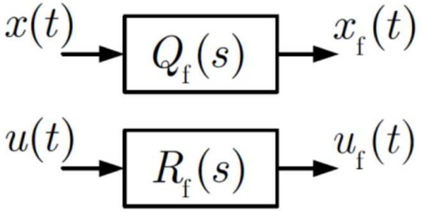
- The cost function can be rewritten as

$$
J(u) = \frac{1}{2\pi} \int_0^{\infty} \left(X_{\mathrm{f}}(j\omega)^{\mathsf{H}} X_{\mathrm{f}}(j\omega) + U_{\mathrm{g}}(j\omega)^{\mathsf{H}} U_{\mathrm{g}}(j\omega) \right) d\omega \longleftarrow \textbf{Frequency domain}
$$

$$
J(u) = \int_0^{\infty} \left(x_{\mathrm{f}}(t)^{\top} x_{\mathrm{f}}(t) + u_{\mathrm{g}}(t)^{\top} u_{\mathrm{g}}(t) \right) dt \longleftarrow \textbf{Time domain}
$$

Frequency Shaping Optimal Control

- The new variables can be interpreted as the output of filters



- The state representation of the filters are

$$\begin{aligned}\dot{z}_Q(t) &= A_Q z_Q(t) + B_Q x(t)\\ x_f(t) &= C_Q z_Q(t) + D_Q x(t)\end{aligned}$$

$$\begin{aligned}\dot{z}_R(t) &= A_R z_Q(t) + B_R u(t)\\ u_f(t) &= C_R z_R(t) + D_R u(t)\end{aligned}$$

- With the filters above and the original state space representation of the system, an extended state space representation can be formulated as

$$\underbrace{\begin{bmatrix}\dot{x}(t)\\ \dot{z}_Q(t)\\ \dot{z}_R(t)\end{bmatrix}}_{\dot{x}_e} = \underbrace{\begin{bmatrix}A & 0 & 0\\ B_Q & A_Q & 0\\ 0 & 0 & A_R\end{bmatrix}}_{A_e} \underbrace{\begin{bmatrix}x(t)\\ z_Q(t)\\ z_R(t)\end{bmatrix}}_{x_e} + \underbrace{\begin{bmatrix}B\\ 0\\ B_R\end{bmatrix}}_{B_e} u(t)$$

Frequency Shaping Optimal Control

- The cost function can be redefined using these new variables as

$$J(u) = \int_0^{\infty} \Big(x_e(t)^\top Q_e x_e(t) + 2u(t)^\top N_e x_e(t) + u(t)^\top R_e u(t) \Big) dt$$

where Q_e , N_e, R_e are defined as

$$Q_e = \begin{bmatrix} D_Q^\top D_Q & D_Q^\top C_Q & 0 \\ C_Q^\top D_Q & C_Q^\top C_Q & 0 \\ 0 & 0 & C_R^\top C_R \end{bmatrix} \qquad N_e = \begin{bmatrix} 0 & 0 & D_R^\top C_R \end{bmatrix} \qquad R_e = D_R^\top D_R$$

- The solution to this system is the following Riccati equation

$$A_e P_e + P_e A_e - (B_e^\top P_e + N_e)^\top R_e^{-1} (B_e^\top P_e + N_e) + Q_e = 0$$

- The optimal input to the system is

$$u_{opt}(t) = -R_e^{-1} (B_e^\top P_e + N_e) x_e(t)$$

Frequency Shaping Optimal Control

- Considering the extended system outputs

$$y_{\mathrm{e}}(t) = C_{\mathrm{e}} x_{\mathrm{e}}(t) + D_{\mathrm{e}} u(t)$$

where

$$C_{\mathrm{e}} = \begin{bmatrix} C & 0 & 0 \\ 0 & I_{n_Q} & 0 \\ 0 & 0 & I_{n_R} \end{bmatrix} \qquad D_{\mathrm{e}} = \begin{bmatrix} D \\ 0 \\ 0 \end{bmatrix}$$

- Considering the constraint that only the outputs are available (optimal output feedback control)

$$u(t) = K y_{\mathrm{e}}(t)$$

- The optimal gain can be found by solving the following system of equations

$$K = -R_{\mathrm{e}}^{-1}(B_{\mathrm{e}}^{\top} P + N_{\mathrm{e}})\Lambda C_{\mathrm{e}}^{\top}(C_{\mathrm{e}}\Lambda C_{\mathrm{e}}^{\top})^{-1} \quad \textbf{(E1)}$$

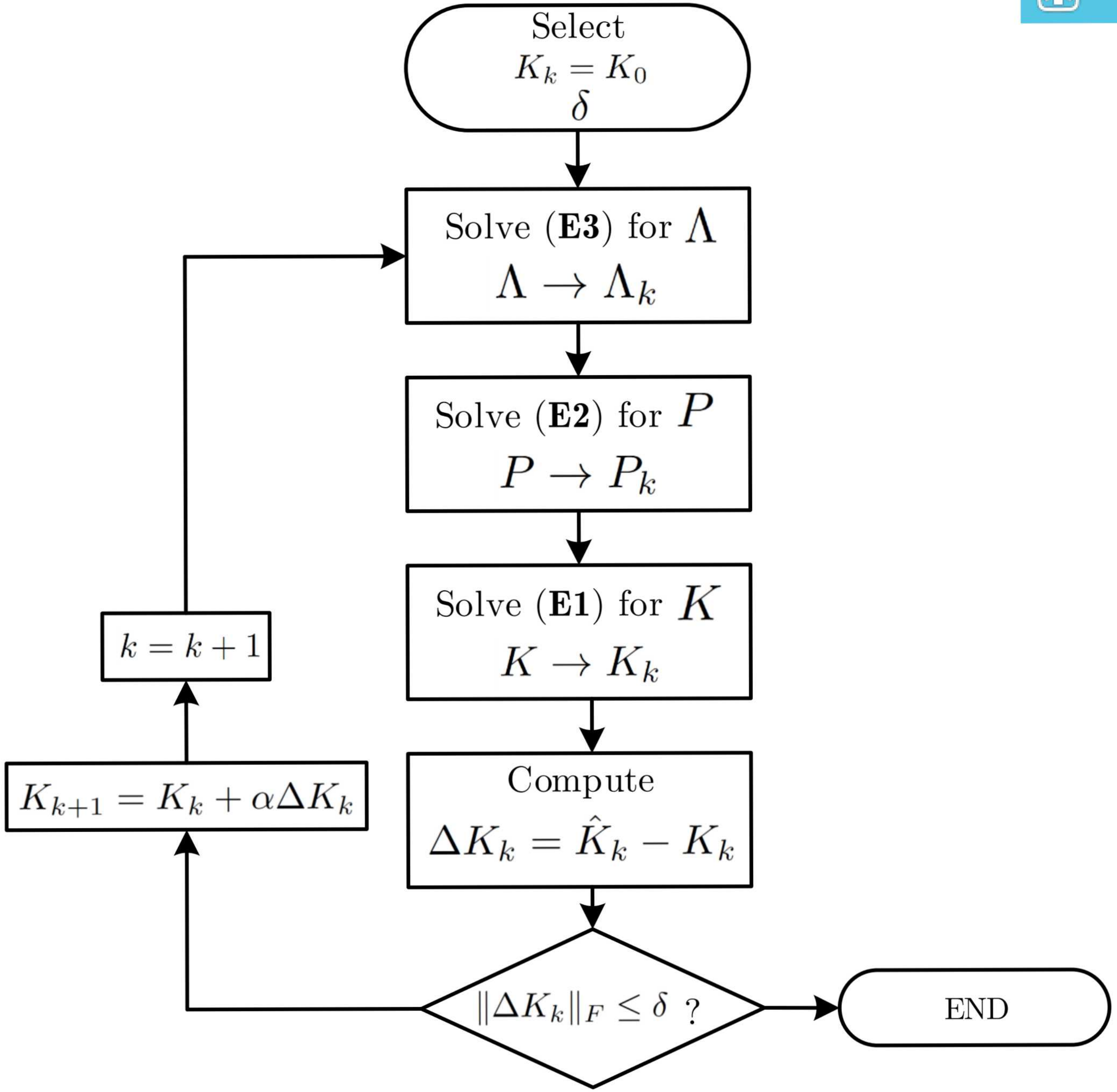
Lyapunov-type:

$$0 = Q_{\mathrm{e}} + C_{\mathrm{e}}^{\top} K^{\top} N_{\mathrm{e}} + N_{\mathrm{e}}^{\top} K C_{\mathrm{e}} + C_{\mathrm{e}}^{\top} K^{\top} R_{\mathrm{e}} K C_{\mathrm{e}} + P(A_{\mathrm{e}} + B_{\mathrm{e}} K C_{\mathrm{e}}) + (A_{\mathrm{e}} + B_{\mathrm{e}} K C_{\mathrm{e}})^{\top} P \quad \textbf{(E2)}$$

$$0 = (A_{\mathrm{e}} + B_{\mathrm{e}} K C_{\mathrm{e}})\Lambda + \Lambda(A_{\mathrm{e}} + B_{\mathrm{e}} K C_{\mathrm{e}})^{\top} + X_0 \quad \textbf{(E3)}$$

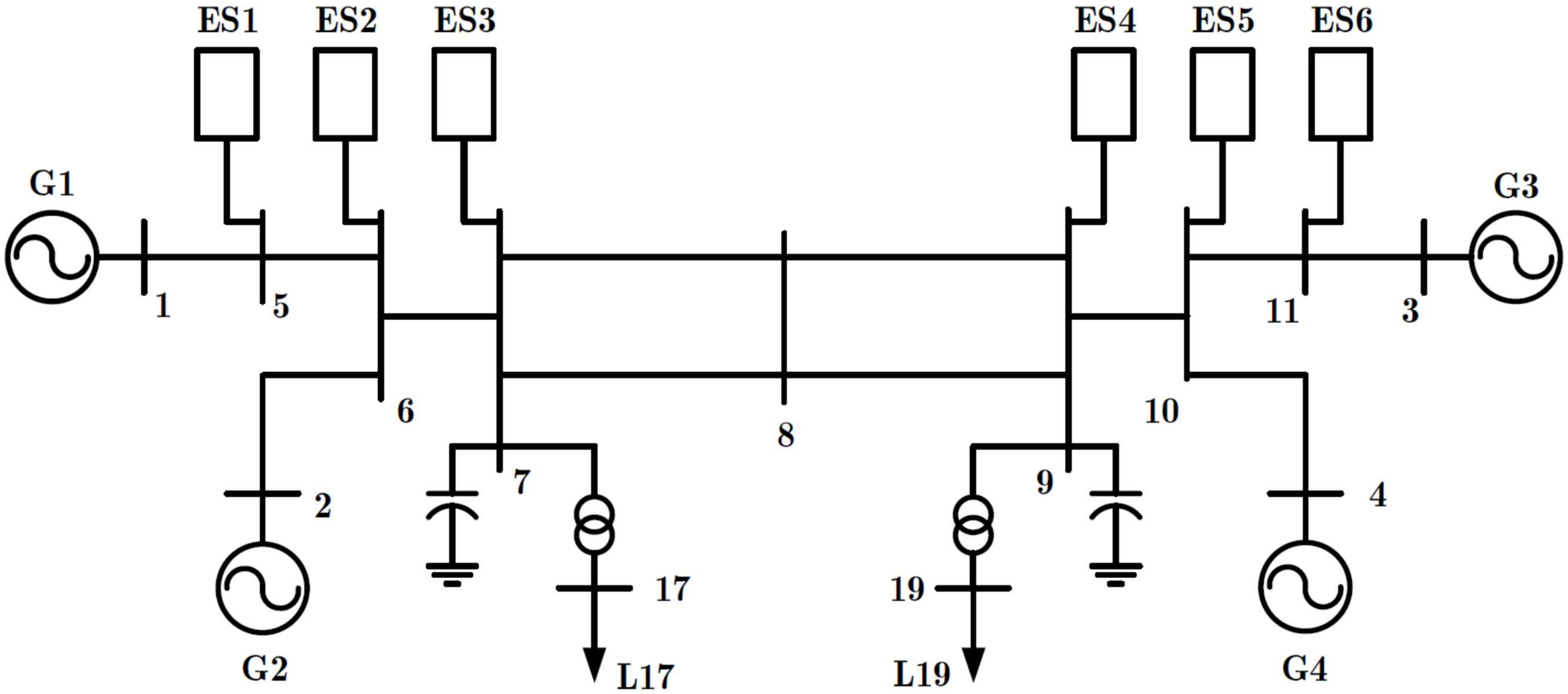
Numerical Solution

- The implemented algorithm follows the form of a classic Anderson-Moore Algorithm



Controller Design

- Test system: two-area, four-machine power system with six energy storage devices



$x \in \mathbb{R}^{28}$

$y \in \mathbb{R}^4$ (machine speeds)

$u \in \mathbb{R}^6$ (actuators)

- The power system has a dominant inter-area oscillation that is poorly damped
- The mode is at $-0.221 \pm j3.435$ (with a damping of 2.8% and a freq. around 0.55Hz)

Filter Design

- Inter-area oscillations are in a frequency range of 0.1 and 1 Hz
- The filter to weight the states is defined as

$$Q_f(s) = q_f(s) I_p C$$

where $q_f(s)$ is a fourth order Bessel filter of the form

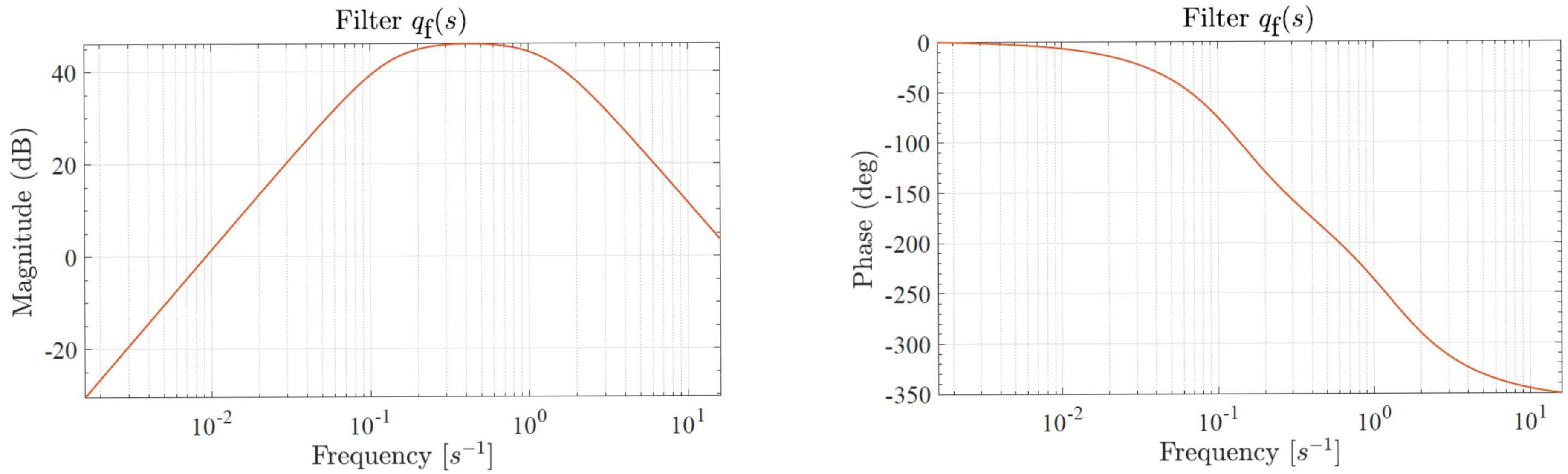
$$q_f(s) = \frac{\gamma_Q a s^2}{s^4 + b_3 s^3 + b_2 s^2 + b_1 s + b_0}$$

with

$a = 75.18$ $\quad b_2 = 89.39$

$b_0 = 50.5$ $\quad b_3 = 15.02$

$b_1 = 106.7$ $\quad \gamma_Q$

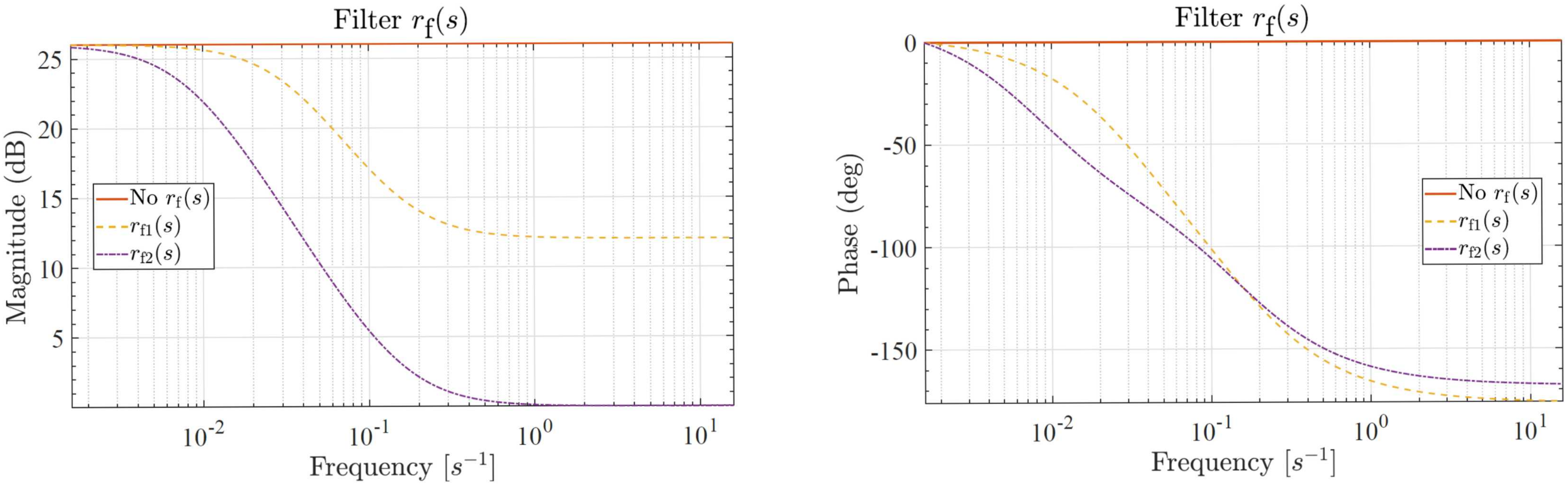


Filter Design

- The filter to weight the input signals $$r_{\mathrm{f}}(s) = \frac{\gamma_R(s - z_r)}{T_r s + 1}$$

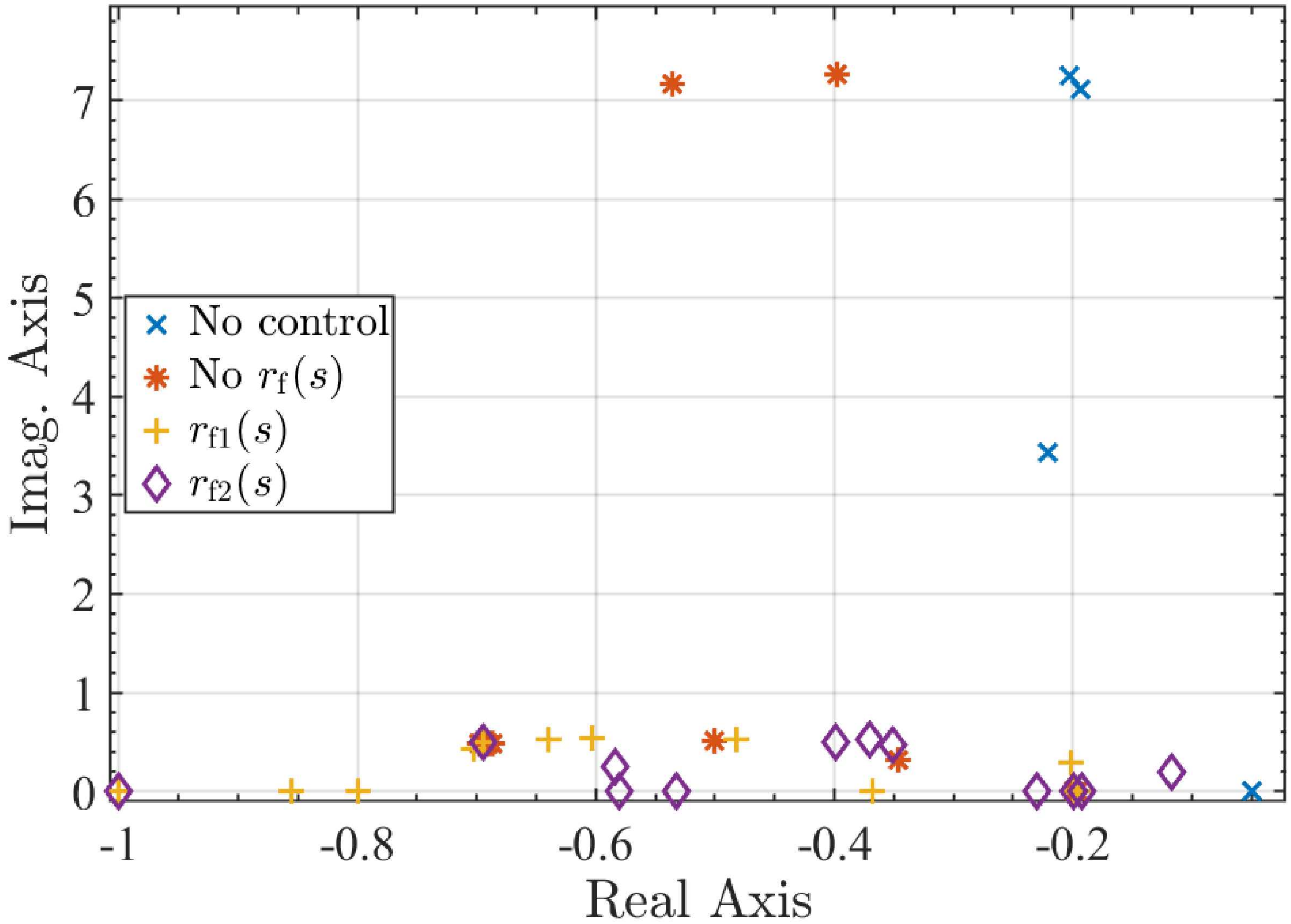
  where γ_R is a constant that determines the weight given to this filter

- This work explores three different forms of $r_{\mathrm{f}}(s)$
  - a. No filter case $\longrightarrow$ $r_{\mathrm{f}}(s) = \gamma_R$
  - b. case with $\longrightarrow$ $z_r = 1$ $T_r = 5$ named r_{f1}
  - c. case with $\longrightarrow$ $z_r = 1$ $T_r = 20$ named r_{f2}



Linear System

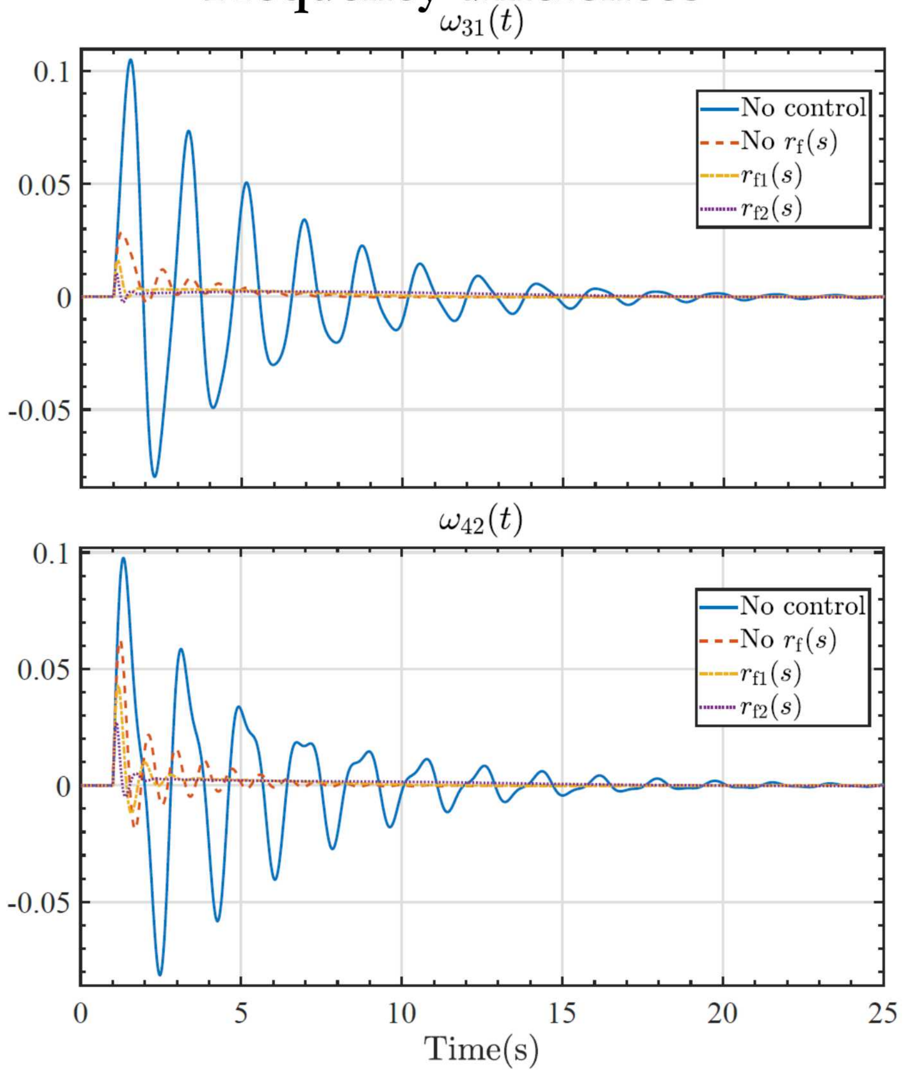
- The eigenvalues of the system for all cases studied



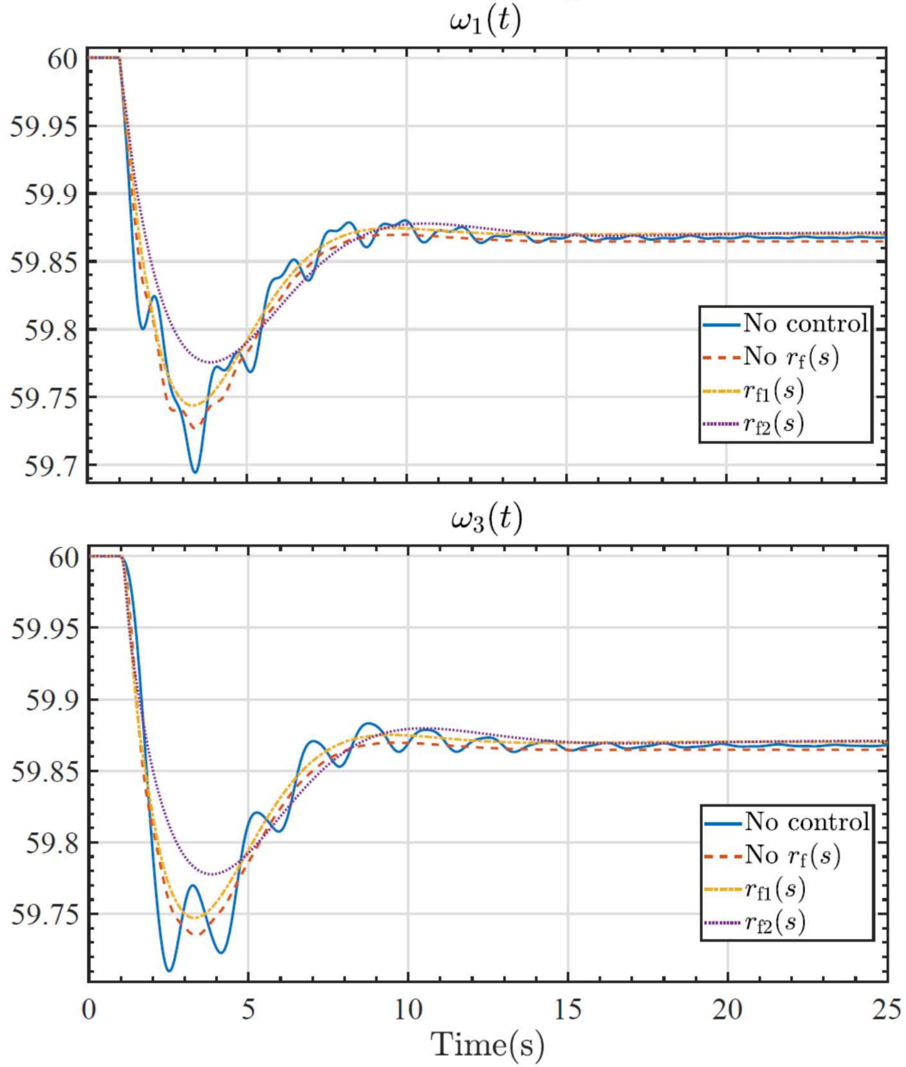
Results in Time Domain

- Time domain simulations were carried out to show how the proposed controllers damp the inter-area oscillations of the 4-machine test system

Frequency differences

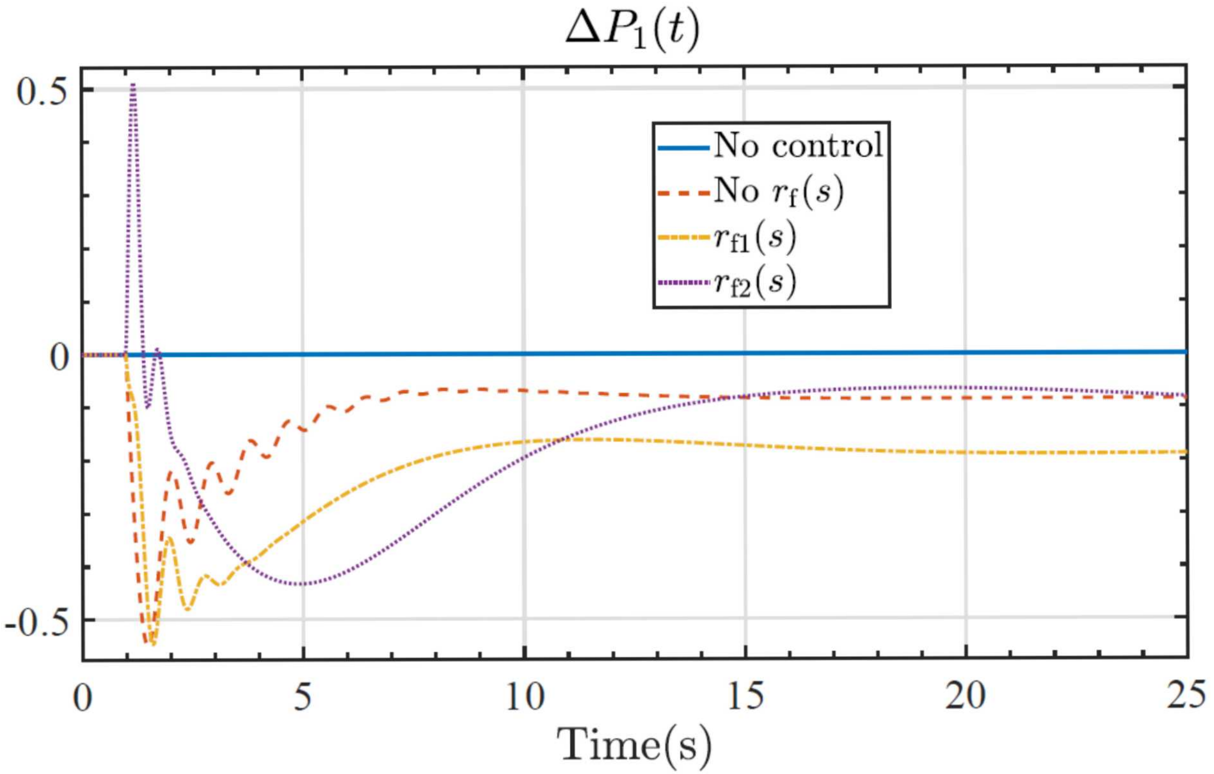


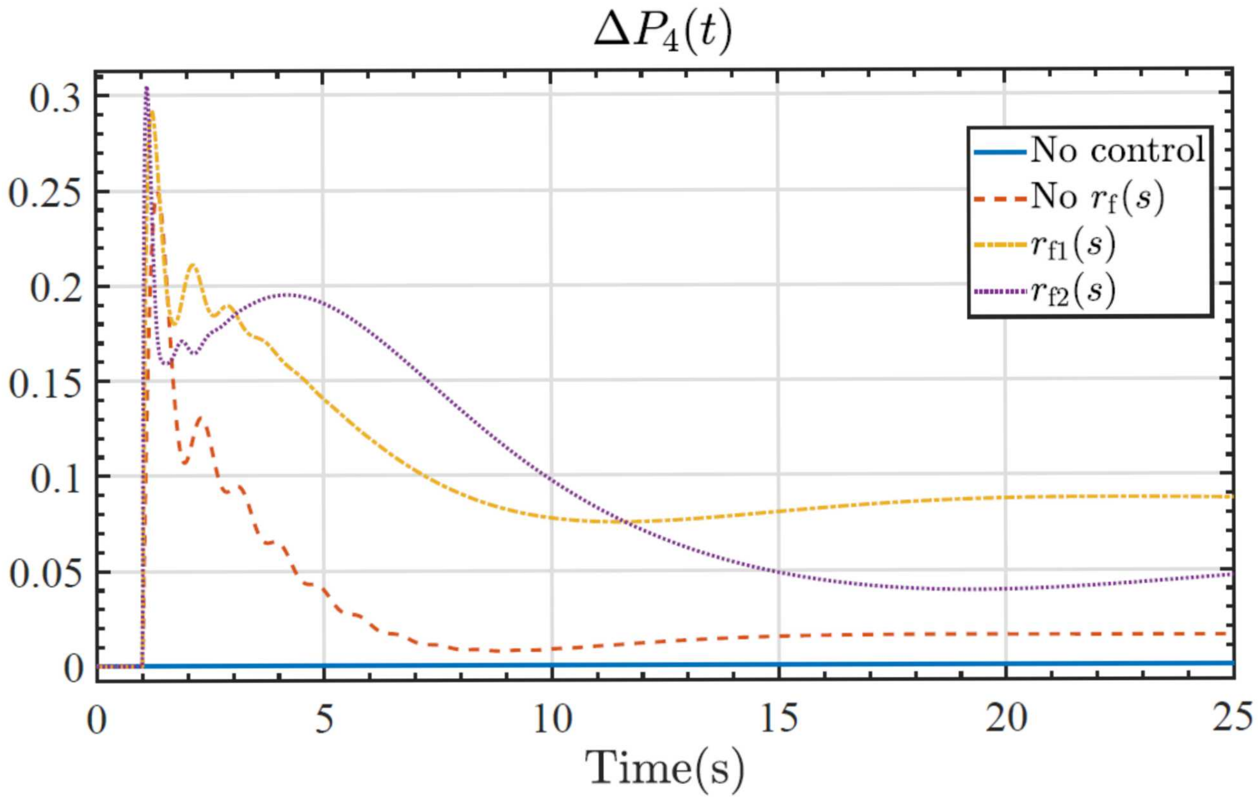
Absolute frequencies



Results in Time Domain

- Power injection of the actuators to achieve a control action





Conclusions

- The paper presents a frequency-shaped approach to compute an optimal controller to damp power systems inter-area oscillations
  - The method was selected because with it filters can be selected to emphasize the frequency interval of inter-are oscillations. The paper shows how to select those filters.
  - The approach was based on optimal output feedback because only machine speeds are considered as the available information.
- The paper also analyzes how the filter can be adjusted to not only damp the system inter-area oscillations but also to modify the primary frequency regulation of the system
- The work presented the effectiveness of the proposed approach on a small test power system
- A future avenue of research of this work is to include uncertainty (noise, parameter uncertainty) into the control approach.

Acknowledgment

- This research was funded by the United States Department of Energy (DoE), Transmission Reliability program

Thank You!

Contact:
Felipe Wilches-Bernal
phone: (505) 845-8292
email: fwilche@sandia.gov