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Optimal Control of Distributed Networked Energy Storage for Improved Small-Signal Stability

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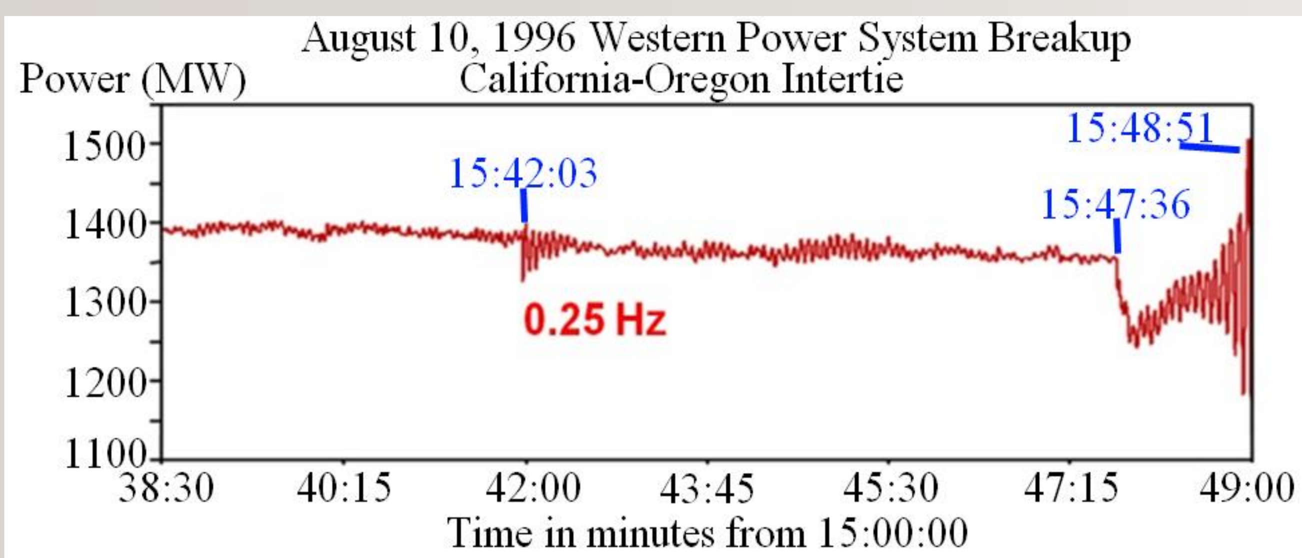
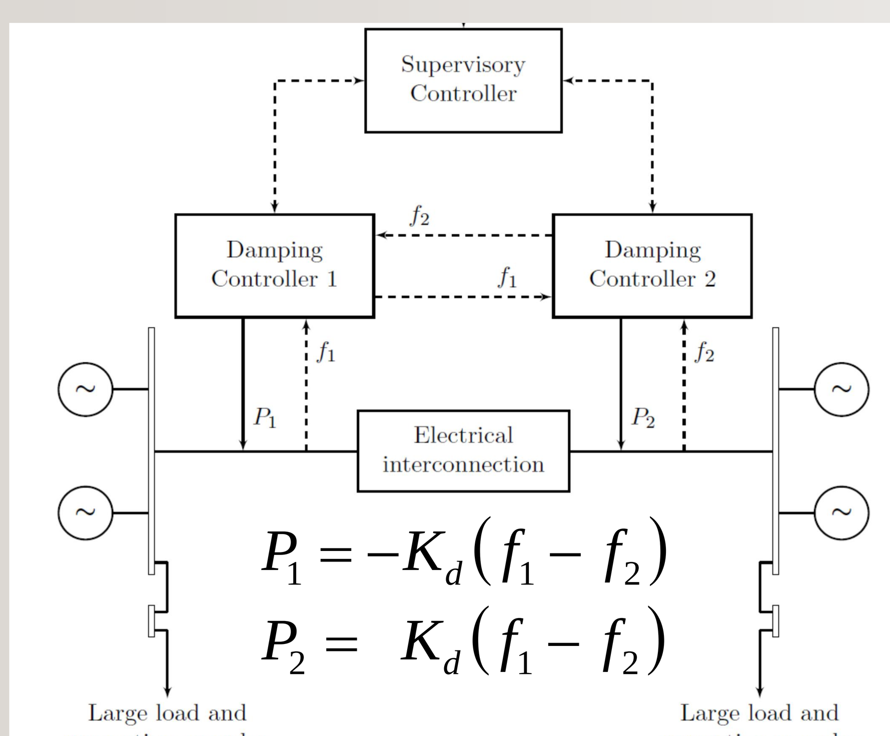
BACKGROUND - For large generation and load complexes separated by long transmission lines, the propensity for complex inter-area oscillations increases. These oscillations have been identified as a hazard for utility systems since they may cause damage to equipment or restrictions on power flows. These oscillations are described by mode frequency, mode shape, and damping ratio. Engineering solutions are needed to mitigate these oscillations.

The 1996 west coast blackout in the U.S. was partially attributed to undamped inter-area oscillations.



PREVIOUS RESEARCH – Previous research identified real power modulation between two areas using energy storage based damping control nodes or High Voltage DC transmission as promising approaches to mitigate inter-area oscillations. Recent work has begun to generalize the approach for $N_D>2$ nodes. The benefits of this approach were illustrated in simulation for systems with $N_D>2$ nodes; however, the network feedback of frequency information was not assumed to have time delay in these. For utility assets and closed networks, delays are short. In a distributed application however, multiple routers, network congestion and security certification steps may incur much longer delays in practice.



PROJECT GOALS – This work aims to develop and demonstrate a robust method to compute the damping control gains for distributed energy storage systems that accounts for network time delays.

CONTROL APPROACH – A Structured Control Algorithm (SCA) is applied wherein inter-area oscillations are assigned a mathematical penalty, a 'cost', and an algorithm determines the gains K_d at each node such that the system cost is minimized. The method requires a linearized system model and a cost function to be defined. The dynamic effect of time delay is incorporated into the state model using the Padé approximation. In practice, energy storage systems modulate power as a function of these gains with feedback from local and remote frequency measurements.

$$\underset{K_d}{\text{minimize}} \quad J = \int_0^{T_f} \left(x^T Q x + u_d^T R u_d \right) d\tau$$

subject to:

(1) $\dot{x}(t) = Ax(t) + B_q q(t) + B_d u_d(t)$

(2) $y(t) = \begin{bmatrix} \Delta\omega_1 & \Delta\omega_2 & \cdots & \Delta\omega_m \end{bmatrix}^T$

(3) $u_d(t) = -K_d y(t)$

(4) $Q \geq 0$ (penalizes freq differences)

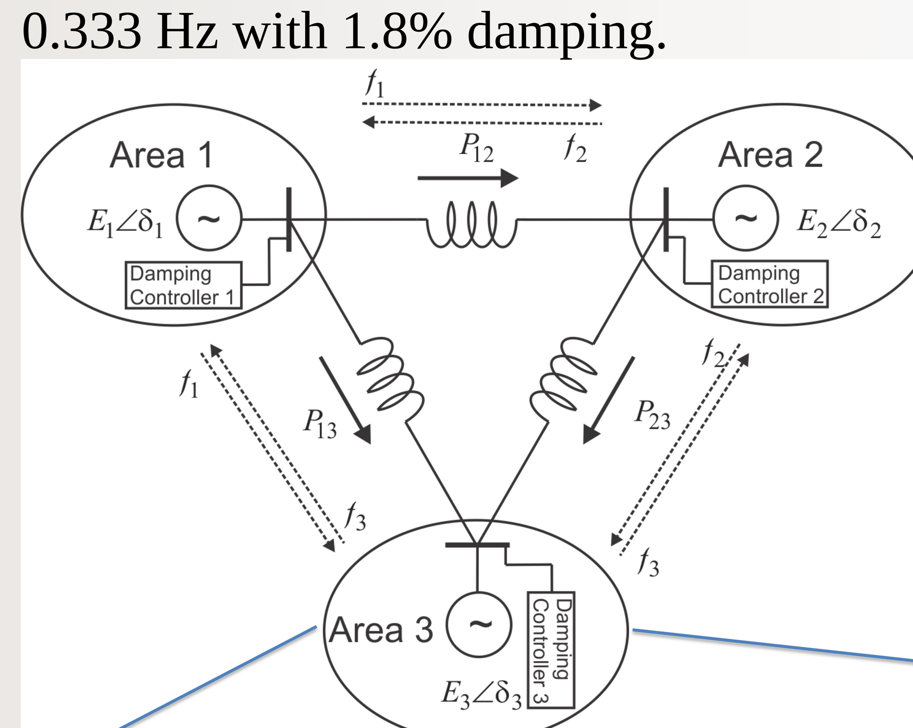
(5) $R > 0$ (penalizes control energy)

PADÉ APPROXIMATION – This method pertains to the approximation of an irrational transfer function by a rational one. For time delay, in particular, the time delay transfer function is approximated by an n^{th}-order approximation.

$$e^{-sT_d} \approx \frac{1 - k_1 s + k_2 s^2 - \ldots \pm k_n s^n}{1 + k_1 s - k_2 s^2 + \ldots \mp k_n s^n}$$

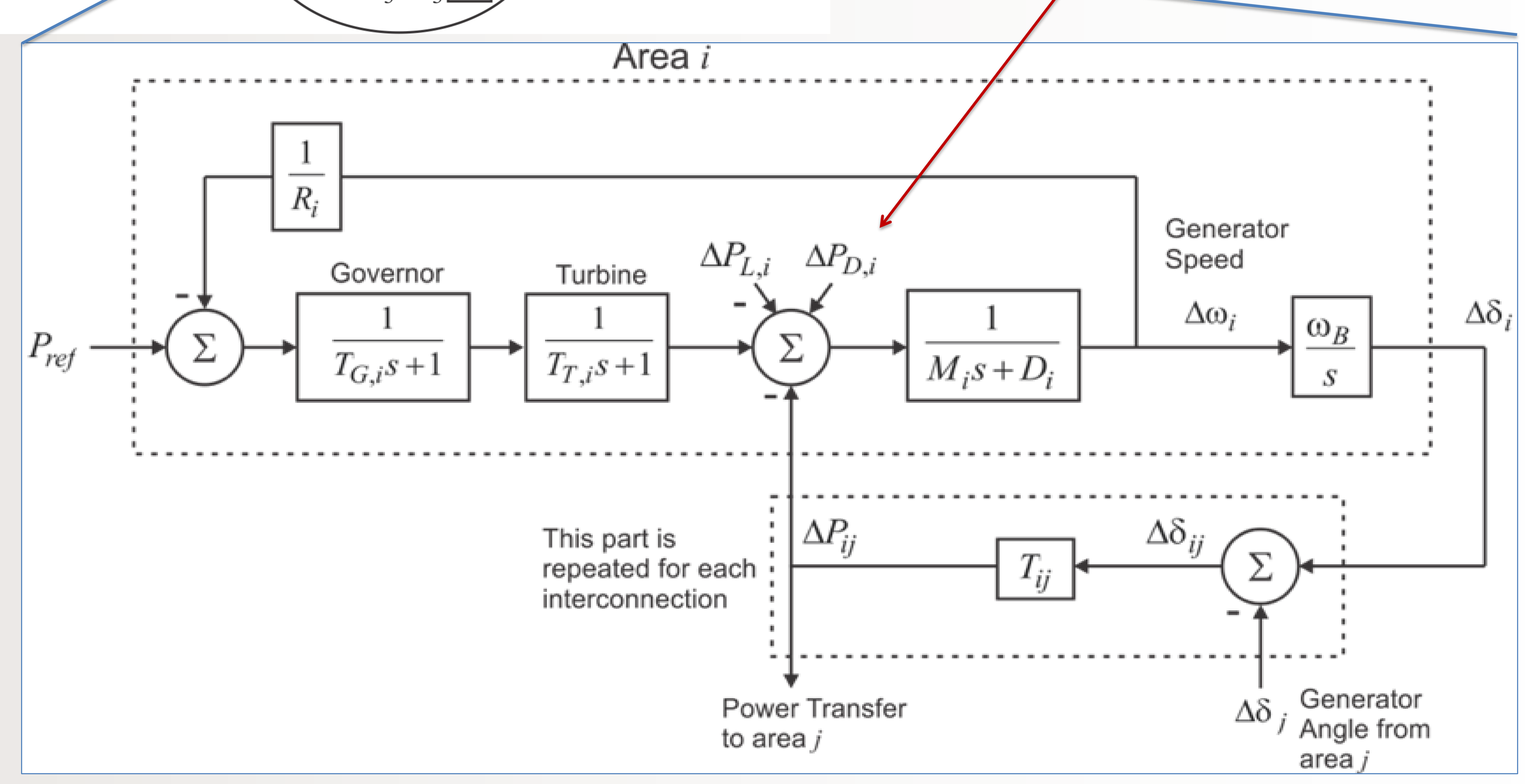
The Padé approximation is incorporated into the state model, thus allowing network time delay to be compensated for in the optimization.

EXAMPLE SYSTEM – A Three-area system is considered wherein each area includes droop, speed governor control, turbine and rotor dynamics and transmission to the other areas. In addition, the model includes long asymmetric network time delays of 0.5-1.5 sec from one area to another. This system has two dominant electromechanical modes at 0.301 Hz with 9.1% damping and 0.333 Hz with 1.8% damping.

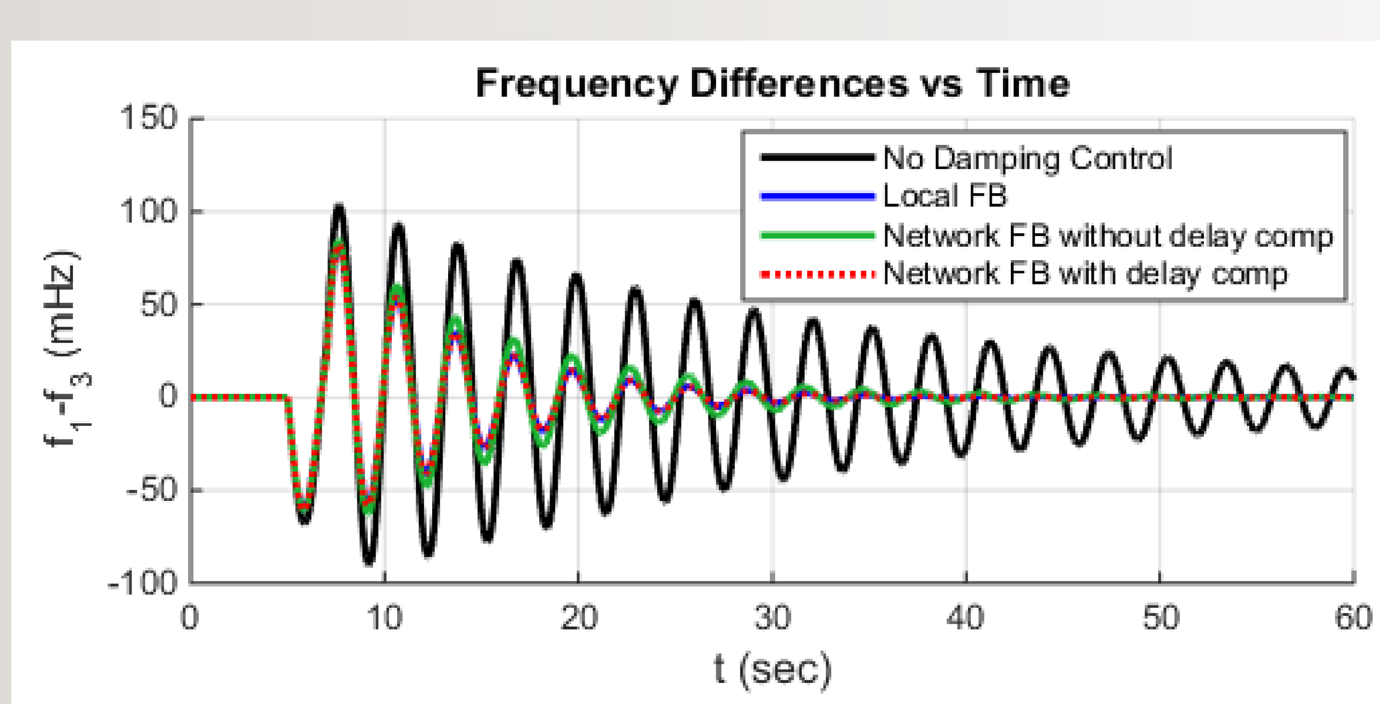


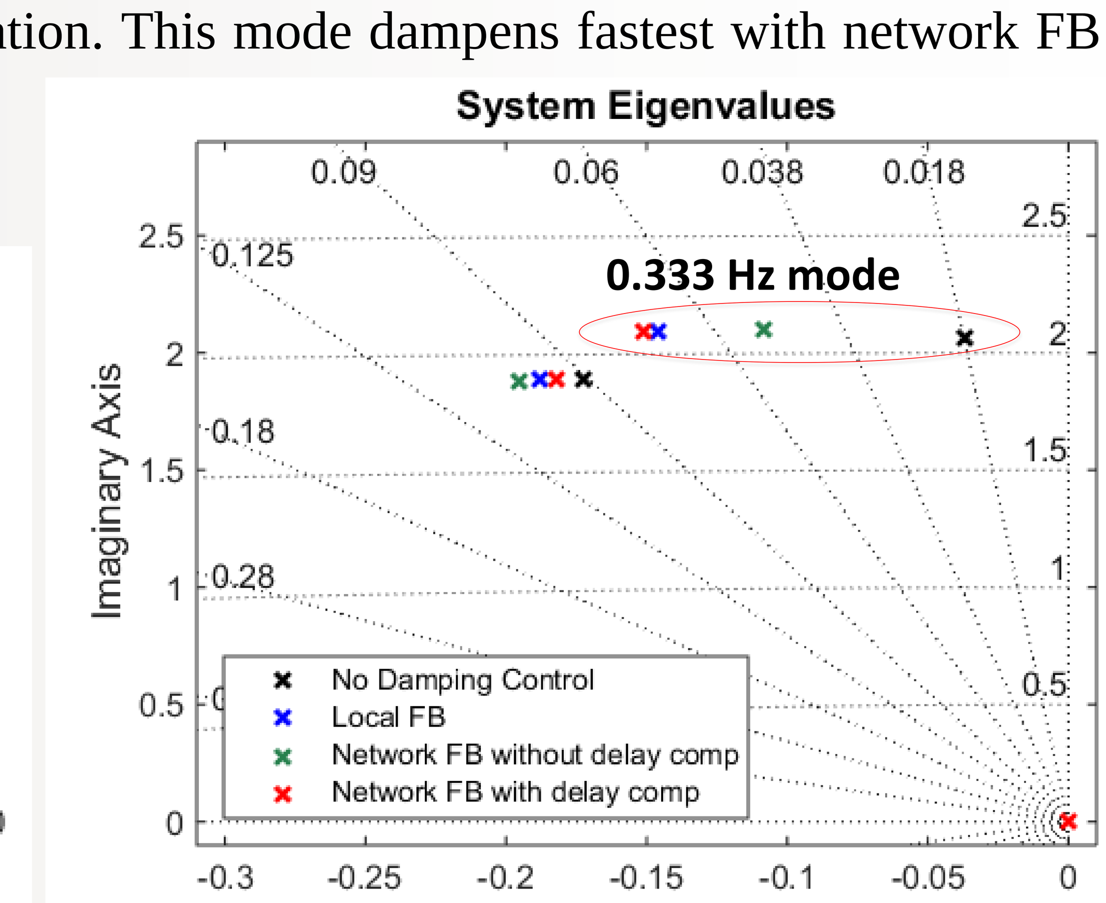
Damping torque applied by energy storage considers local and remote feedback

$$\Delta P_{D,i} = -\sum_{j=1}^{n} K_{d,ij} f_j \left(t - T_{d,j} \right)$$



SIMULATION RESULTS – The optimization was formulated to provide damping to both modes but to prioritize the lightly damped 0.333 Hz mode. Damping control was evaluated for local feedback (FB), network FB without delay compensation and network FB with delay compensation. Eigenvalues are compared for each, and various cases are evaluated in simulation for a simple impulse response. Network FB with delay compensation provides the best damping with less control energy at the specified mode. The 0.333 Hz mode is observable in the f_1-f_3 oscillation. This mode dampens fastest with network FB with delay compensation.





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