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Damping of Inter-Area Oscillations via Modulation of Aggregated Loads

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Presentation outline

- Introduction
- Methodology for load and generator aggregation
  - Load Clustering
  - Generator aggregation
- System identification
- Optimal output feedback control design
- Time simulations on a test power system
- Conclusions

Introduction

- Sparsely interconnected power systems experience oscillations between separate geographical areas.
- Known as inter-area oscillations, in this phenomena generators of one area oscillate against those in another area.
- These oscillations are the product of weak connections between the areas or high power transfers (strains the power system).
- If not properly mitigated these oscillations can destabilize the system. Example of this effect: the 1996 west coast blackout.

Introduction

- A current solution to address the problems posed by inter-area oscillations is to limit the amount of power transfer in critical tie lines. This solution is not optimal as infrastructure is being underutilized.
- Another common solution is to include power system stabilizers (PSSs) in conventional generators spread throughout the system. PSSs act on the excitation system of the machine. They use local signals.
- Research has shown that inter-area oscillation damping can be achieved by modulating power system components: FACT devices, Energy Storage, Wind and Solar energy systems, and HVDC links.

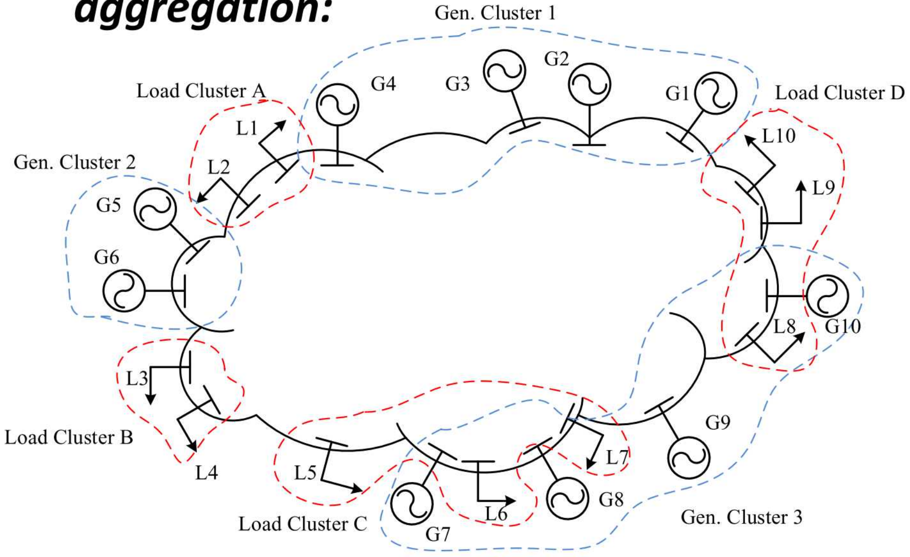
Introduction

- This work proposes another method for damping inter-area oscillations
- The idea is to modulate load (the demand side of the system) to provide damping to these oscillations.
- The proposed controller also uses wide area measurements (assumed to come from phasor measurement units PMUs).

Load and Generator Aggregation

- Each *load* is generally small and does not have the capacity of affecting the entire system.
- Idea in this work is to aggregate or cluster loads to increase the effect that each cluster has on the dynamics of the system.
- Signals used for feedback are averaged generator speeds. The average is computed from a group of generators.

Example of load and gen aggregation:



Load and Generator Aggregation

- Averaging generator speeds (within an area):

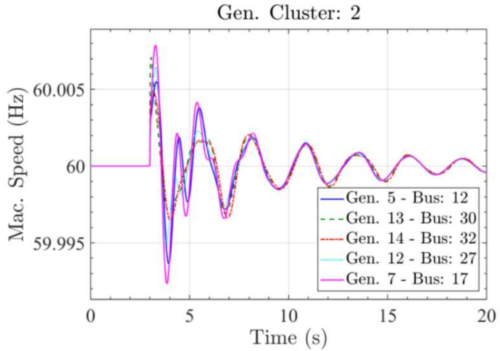
$$\omega_a = \frac{1}{H_a} \sum_{i \in \{\Omega_a\}} H_i \omega_i$$

Set of generators in *area* a

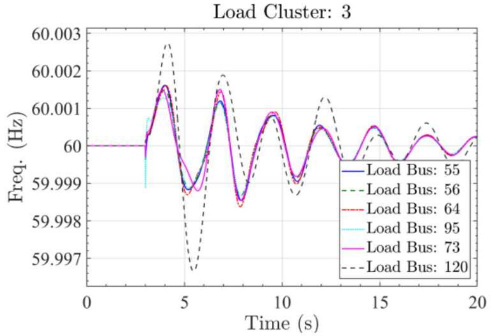
Ω_a

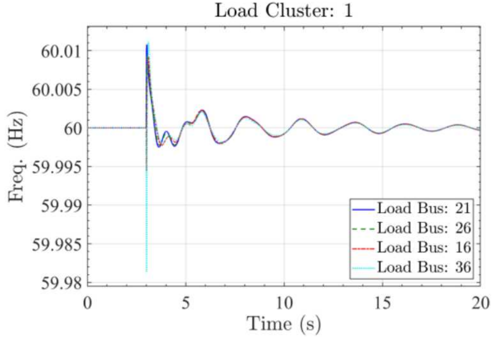
where:

$$H_a = \sum_{i \in \{\Omega_a\}} H_i$$



- Example of clustering loads:





System Identification

- The effect that load clusters have on the dynamics of the system needs to be determined.
- To do so this works proposes to perform a set of probing tests. Each set consist of modulating the active power of every load at a particular cluster with the same signal

$$P_{i,\mathrm{cmd}}(t) = AP_{i,\mathrm{schd}}\,x_{\mathrm{prb}}(t) \qquad \forall i \in \mathcal{C}$$

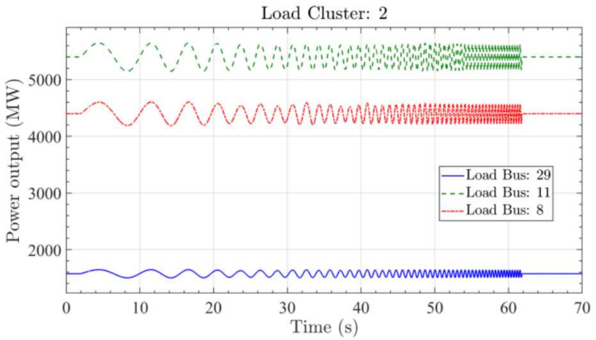
$\mathcal{C}$ is any load cluster

Steady-state power consumption

probing signal

System Identification

- Modulating a cluster of loads with the chirp signal is observed as follows



- When such probing occurs the average frequency at each area is computed.

- Having the chirp signal as input and the output being set of area frequencies a system identification approach is used.

- In this work the system identification method used is the Eigenvalue Realization Algorithm (ERA). The aim is to obtain a system of the form

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

$x \in \mathbb{R}^n$ the state

$u \in \mathbb{R}^m$ control input (number of clusters of loads)

$y \in \mathbb{R}^p$ the output (generator speeds)

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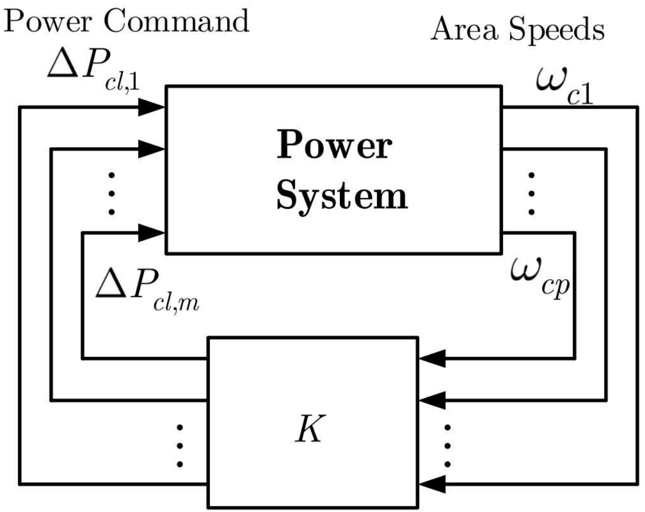
Optimal Output Feedback Control

- Control approach: modulate clusters of loads to enhance the small-signal stability of the system (damp inter-area oscillations)



- How to optimally control the loads?
- Solution is found in optimal control theory.
- Because the only information available for control is those of the area speeds optimal output feedback control is selected as the control approach.

Optimal Output Feedback Control

- The control law is

$$u(t) = Ky(t) \quad \text{where} \quad K \in \mathbb{R}^{m \times p}$$

$$u = [\Delta P_{cl,1} \;\dots\; \Delta P_{cl,m}]^\top$$
$$y = [\omega_{a1} \;\dots\; \omega_{ap}]^\top$$

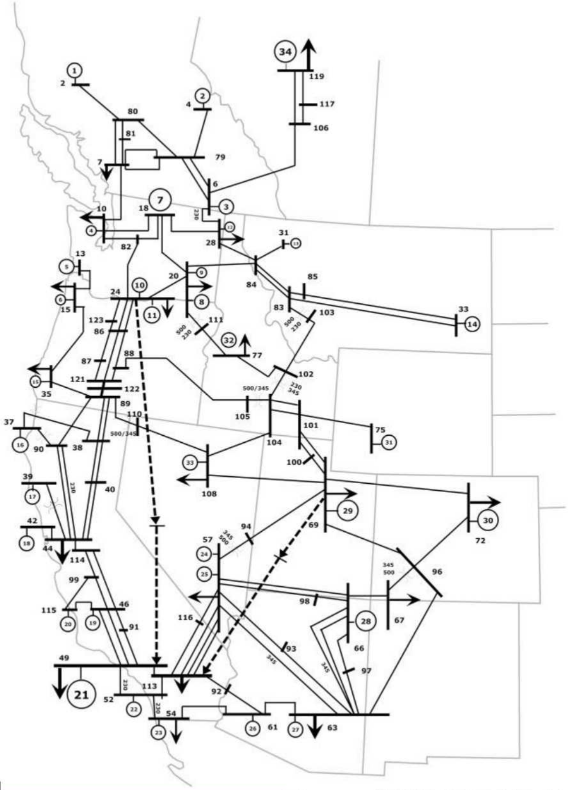
$$K = \begin{bmatrix} k_{11} & k_{12} & \dots & k_{1p} \\ k_{21} & k_{22} & \dots & k_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ k_{m1} & k_{m2} & \dots & k_{mp} \end{bmatrix}$$

- The sum of the rows of K represents the **droop gain** for a particular load cluster.

SIMULATIONS IN TIME-DOMAIN

Test Power System

- Power system model used in this paper is a reduced order representation of the western North American Power System (wNAPS). Known as the Minni WECC,
- The model has:
  - 34 generators
  - 120 buses
  - 19 loads
  - 2 HVDC transmission lines
- This model was custom made to represent the small signal stability dynamics of the actual wNAPS.
- The operating condition in this work has one mode (the North South B or Alberta) with low damping.



System Set up

- Clusters of loads and generators groups in the MinniWECC

TABLE I: Load clusters in the miniWECC

Cluster No.	Loads in the cluster	Total power (MW)
1	L_{21}, L_{26}, L_{16}, L_{36}	5850
2	L_{29}, L_{11}, L_{8}	11375
3	L_{55}, L_{56}, L_{64}, L_{95}, L_{73}, L_{120}	41375
4	L_{78}, L_{43}, L_{109}	17340
5	L_{112}, L_{50}, L_{70}	30075

TABLE II: Generators Areas

Area No.	Generators in Area
1	G_{8}, G_{9}, G_{10}, G_{11}, G_{5}, G_{15}
2	G_{5}, G_{13}, G_{14}, G_{12}, G_{7}
3	G_{22}, G_{30}, G_{25}, G_{24}, G_{28}, G_{27}, G_{23}, G_{34}
4	G_{19}, G_{20}, G_{21}, G_{29}
5	G_{16}, G_{17}, G_{18}, G_{31}, G_{32}, G_{33}
6	G_{1}, G_{2}, G_{3}, G_{4}

Gen. 26 was not assigned to any area (that's where a fault occurs)

Time-Domain Simulation Results

- Using the 5 load clusters presented above as well as the 6 generator areas a set of probing test were performed and a system was identified as follows

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

$x \in \mathbb{R}^{44}$ the state

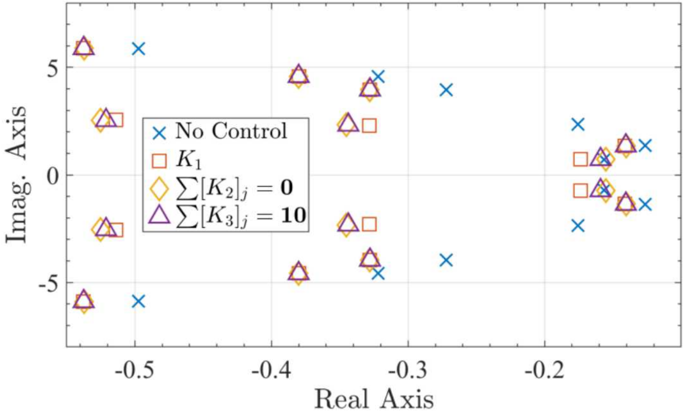
$u \in \mathbb{R}^{5}$ control input (number of loads)

$y \in \mathbb{R}^{6}$ the output (generator speeds)

- Using the identified system 3 controllers were computed using the design approach explained earlier
  - A controller using the regular optimal output feedback control (*K1*)
  - Including the modification that the sum of the rows of the optimal gain is zero (*K2*)
  - Including the modification that the sum of the rows of the optimal gain is 10 (*K3*)

Time-Domain Simulation Results

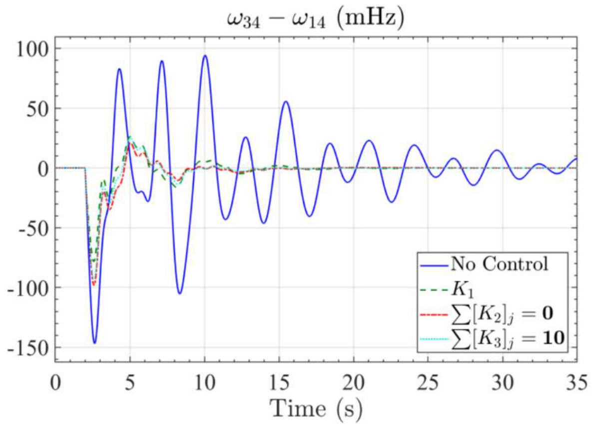
- Eigenvalues of the system for all the different control cases

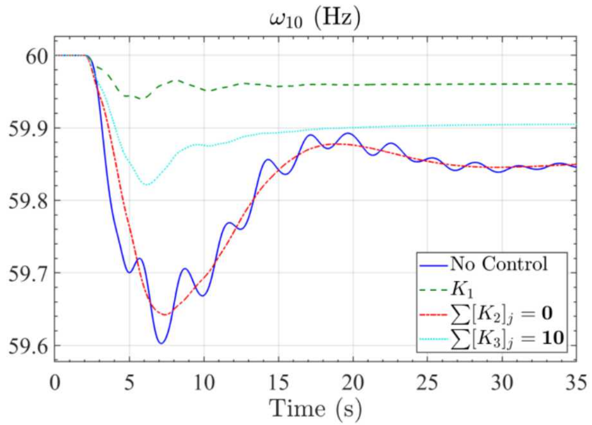


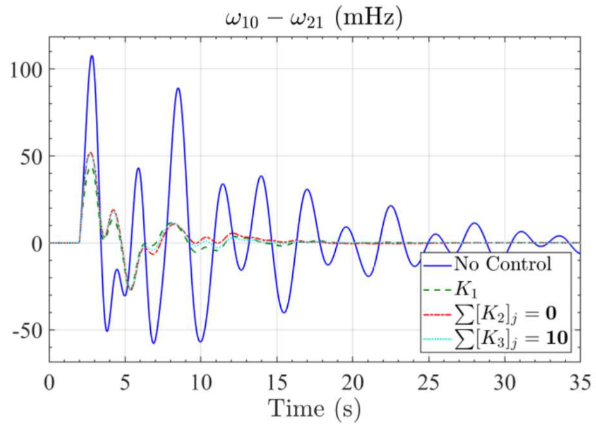
- Using each of the controllers. Two different events were analyzed:
  - Tripping of the Palo Verde generating unit (Gen. 26, Bus 61) at 2 seconds
  - Loss of line between Buses 86 and 87 (within the COI) at 2 seconds

Time-Domain Simulation Results

- Machine speeds and relative machine speeds for the loss of Gen. 26 event

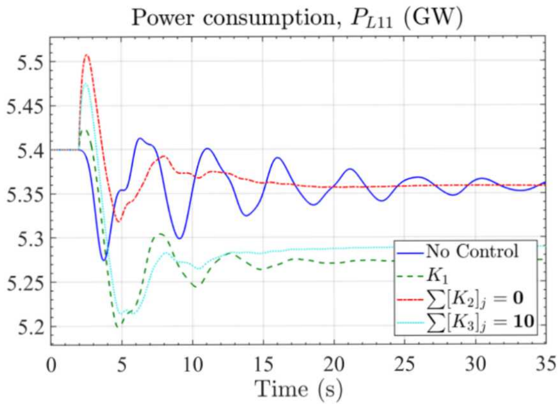


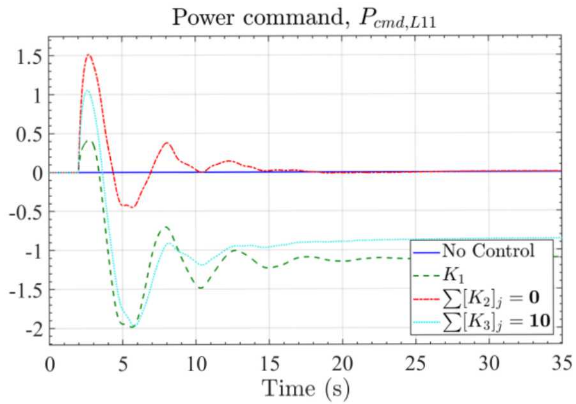




Time-Domain Simulation Results

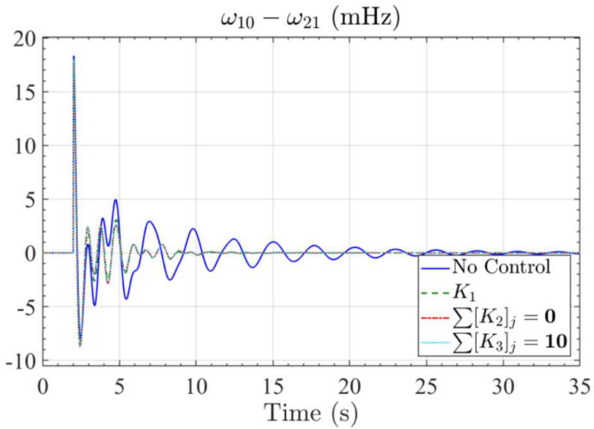
- Power modulation for load 11, in cluster no. 2, for the loss of Gen. 26 event

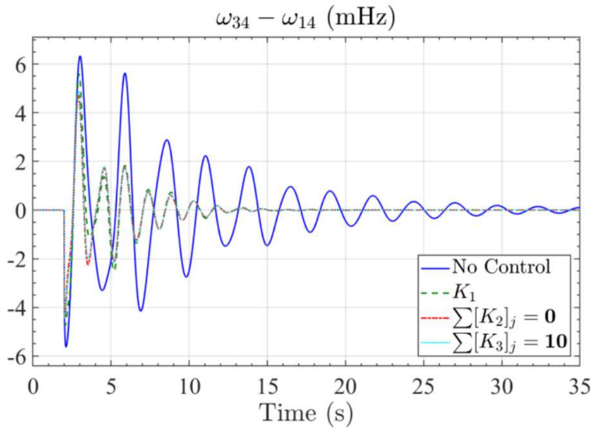


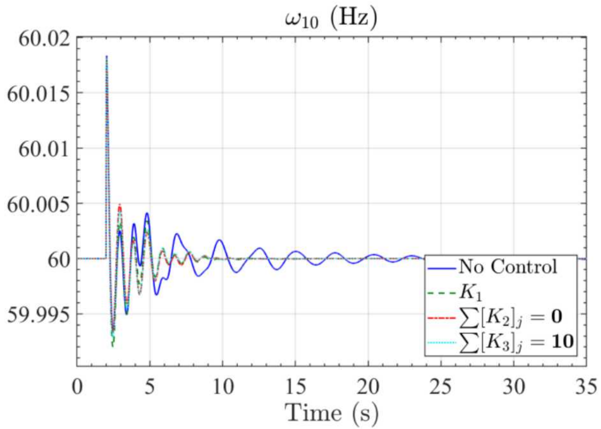


Time-Domain Simulation Results

- Machine speeds and relative machine speeds for the loss of line event.

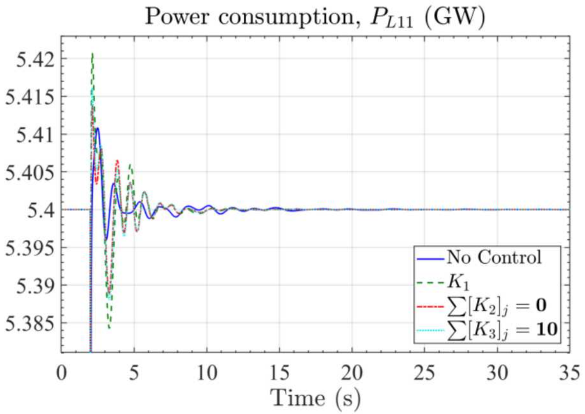


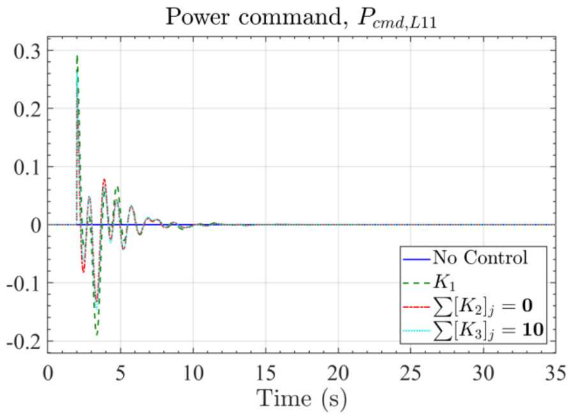




Time-Domain Simulation Results

- Power modulation for load 11, in cluster no. 2,for the loss of line event





Conclusions

- Load can effectively be used as an actuator to damp inter-area oscillations in power systems.
- Aggregating loads is important to achieve dynamic effects on the system with small load modulation.
- Proposed solution ensures a controller that provides inter-area oscillation damping while being inactive to steady-state or global frequency deviations.
- Wide area information is important in the control design

Thank You!

Questions?

Structuring the Optimal Gain

Back up slides

Optimal Output Feedback Control

- Formulation of the optimal output feedback control:

$$\tilde{J} = \mathbb{E}\left\{ \int_0^{\tau} x(t)^\top (Q + C^\top K^\top RKC) x(t) dt + x(\tau)^\top S_f x(\tau) \right\}$$

where $\mathbb{E}\{\cdot\}$ is the expected value and, $\mathbb{E}\{x_0 x_0^\top\} \triangleq X_0$ is the covariance of the initial conditions

- The optimization problem is then formulated as

$$\min_{K} \ \tilde{J}(K, \tau)$$

where K is assumed to exist and is chosen from the set $\mathcal{S}$ of stabilizing gains

$$\mathcal{S} \triangleq \{K \in \mathbb{R}^{m \times p} : \mathrm{Re}\{\lambda(A + BKC)\} < 0\}$$

Optimal Output Feedback Control

- The solution of the OOFC control problem when considering the infinite horizon case $\tau \rightarrow \infty$

and with the following definitions

$$X = x(t)x(t)^\top \qquad \int_0^\infty X \, dt = P \qquad S_f = 0$$

is obtained from the following equations:

$$0 = Q + C^\top K^\top R K + \Lambda(A+BKC) + (A+BKC)^\top \Lambda$$
$$0 = (A+BKC)P + P(A+BKC)^\top + X_0$$
$$0 = \frac{\partial \tilde{J}}{\partial K} = 2\left(RKC + B^\top \Lambda\right) PC^\top$$

Lyapunov like

In this case the optimal gain K^* can be obtained from

$$K^* = -R^{-1}B^\top \Lambda P C^\top (CPC^\top)^{-1}$$

Structuring the Optimal Gain

- Note that the gain can be written as

$$K = \begin{bmatrix} k_{11} & k_{12} & \dots & k_{1p} \\ k_{21} & k_{22} & \dots & k_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ k_{m1} & k_{m2} & \dots & k_{mp} \end{bmatrix}$$

- The optimal modulation for the *i-th* cluster of loads

$$\Delta P_{cl,i} = \sum_{j=1}^{p} k_{ij}\omega_{aj} \qquad \forall i = 1\dots m$$

- Also note that in a power system whose synchronism is preserved as $t \to \infty$ then

$$\omega_{aj}(t) = \omega_F \qquad \forall j = 1\dots p$$

- The sum of the rows of K represents the **droop gain** for a particular load cluster.

Structuring the Optimal Gain

- This work proposes a method to fix the sum on the rows of the control gain while maintaining an optimal control approach to compute it.

Fixing the sum of the rows means: $$K\mathbf{1}_p = \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_m \end{bmatrix} \triangleq \bar{v}$$

- To impose this constraint consider

$T_j \in \mathbb{R}^{p\times n}$ ⟵ matrix with all zeros except those in its jth column which are 1

- The penalty function to be included in the cost function is

$$g(K) = \gamma T_j^\top (K-\Upsilon)^\top (K-\Upsilon) T_j$$ with $$\Upsilon = \bar{v}\frac{\mathbf{1}_p^\top}{p} \qquad \Upsilon \in \mathbb{R}^{m\times p}$$

Parameter that reflect the importance of enforcing the constrain

Structuring the Optimal Gain

- The reformulation of the optimal output feedback control problem is

$$\tilde{J}(K,\tau) = \mathbb{E}\left\{ \int_0^{\tau} x(t)^\top \left(Q + C^\top K^\top R K C + \boxed{\gamma g(K)}\right) x(t)\, dt + x(\tau)^\top S_f x(\tau) \right\}$$

added penalty function

where $\mathbb{E}\{\cdot\}$ is the expected value and, $\mathbb{E}\{x_0 x_0^\top\} \triangleq X_0$ is the covariance of the initial conditions

- The formulation of the problem is the same as

$$\min_{K} \; \tilde{J}(K,\tau)$$

where K is assumed to exist and is chosen from the set $\mathcal{S}$ of stabilizing gains

$$\mathcal{S} \triangleq \{K \in \mathbb{R}^{m\times p} : \mathrm{Re}\{\lambda(A+BKC)\} < 0\}$$

Note that this approach is a **soft constraint approach**

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Structuring the Optimal Gain

The solution of the reformulation of the OFC control problem when considering the infinite horizon case $\tau \to \infty$ and with the following definitions

$$X = x(t)x(t)^\top \qquad \int_0^\infty X\,dt = P \qquad S_f = 0$$

is obtained from the following equations:

$$0 = Q + C^\top K^\top RK + +\gamma T^\top (K - \Upsilon)^\top (K - \Upsilon) + \Lambda(A + BKC) + (A + BKC)^\top \Lambda \quad \textbf{(E1)}$$

Lyapunov like

$$0 = (A + BKC)P + P(A + BKC)^\top + X_0 \quad \textbf{(E2)}$$

$$0 = \frac{\partial \tilde{J}}{\partial K} = 2\left(RKC + B^\top \Lambda\right) PC^\top + 2\gamma KTPT^\top - 2\gamma \Upsilon TPT^\top$$

$$B^\top \Lambda PC^\top - \gamma \Upsilon TPT^\top + RKCPC^\top + \gamma KTPT^\top = 0 \quad \textbf{(E3)}$$

Sylvester equation (a more general type of linear matrix equation)

- These equations can be solved iteratively through a dynamic algorithm