Decentralized and optimal control of inter-area oscillations in power networks

Technische Universität Berlin 2015

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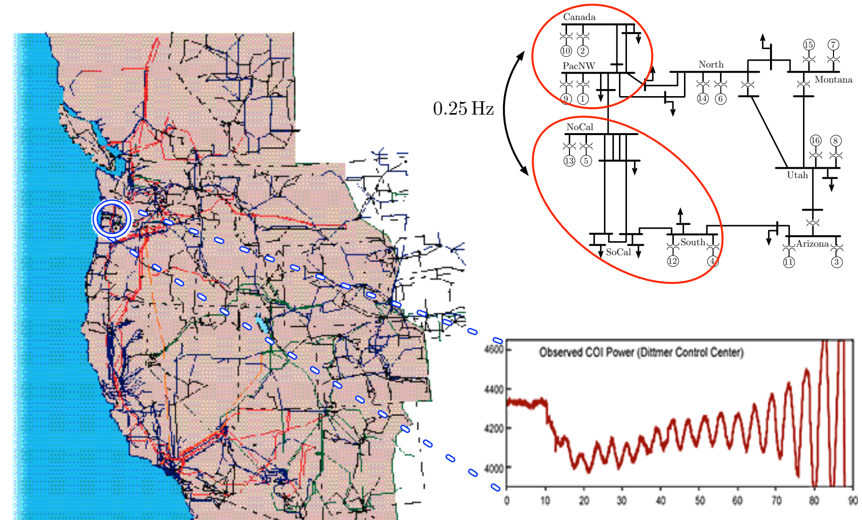
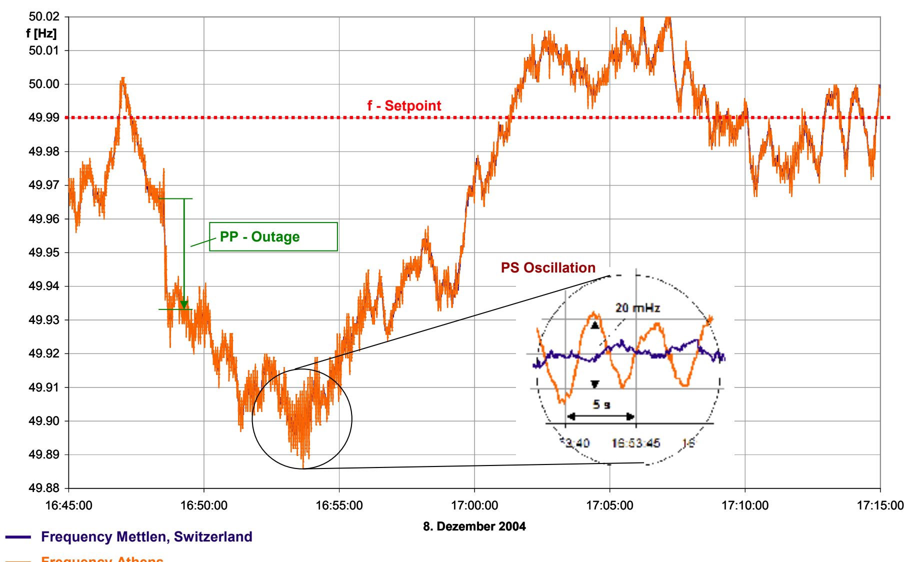
Electro-mechanical oscillations in power networks

Dramatic consequences: blackout of August 10, 1996, resulted from instability of the 0.25 Hz mode in the Western interconnected system



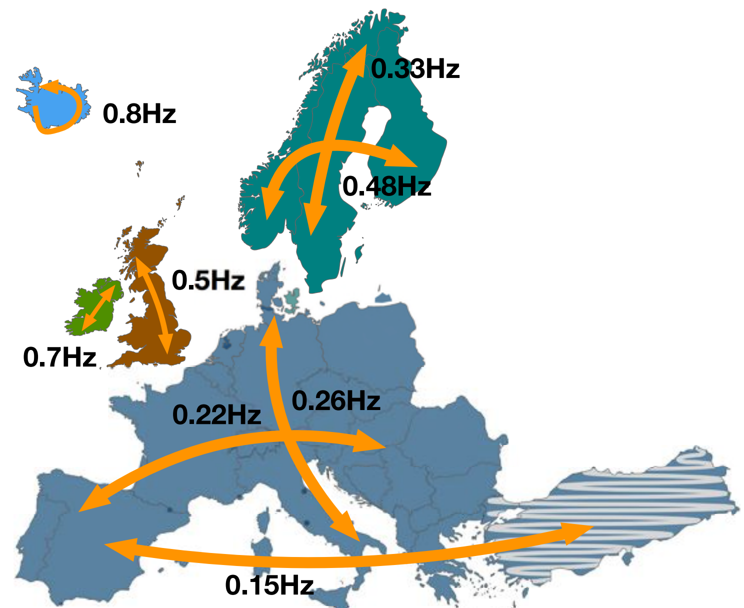
Source: http://certs.lbl.gov

Less dramatic but quite common . . . usually well behaved

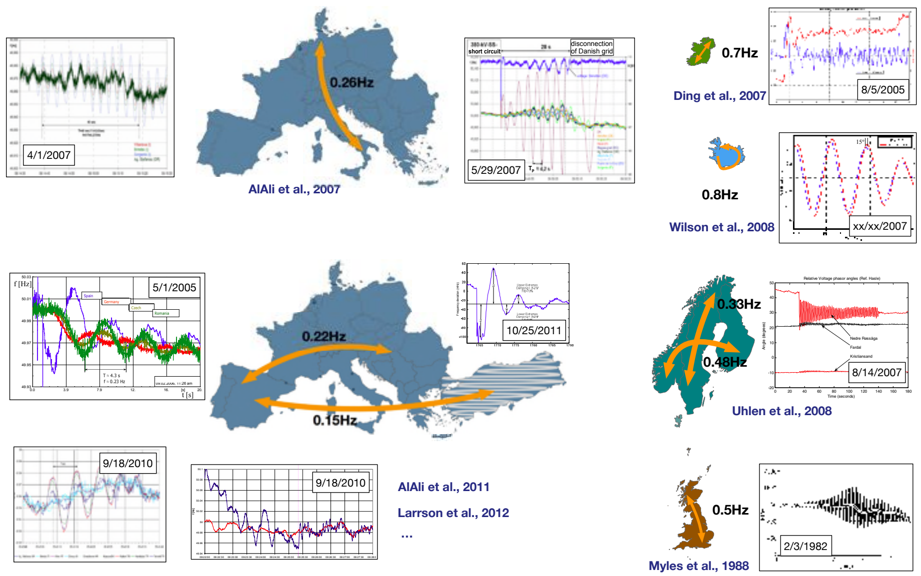


Source: G. Andersson (ETH) & W. Sattinger (Swissgrid)

A few typical inter-area oscillations in Europe



A closer look at some European incidents



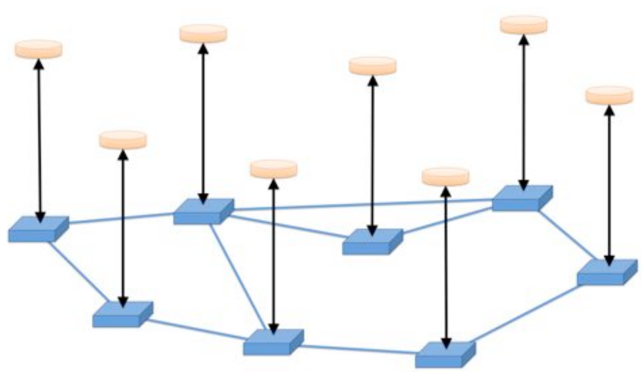
This is not a "solved problem"

Europe:
- transmission network upgrades & expansion,
- renewable generation in remote locations, &
- deregulated markets, ...

United states:
- aging transmission infrastructure,
- sparse grid with load & generation hubs, &
- remote renewables, ...

Remedies against electro-mechanical oscillations

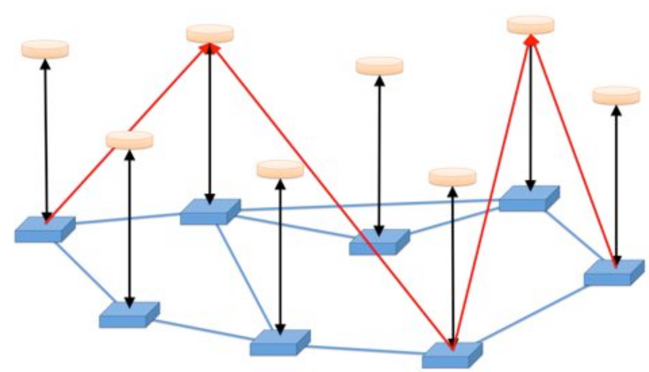
conventional control



- blue layer: interconnected generators
- fully decentralized control implemented locally
  - ☺ effective against local oscillations
  - ☹ ineffective against inter-area oscillations

Remedies against electro-mechanical oscillations

wide-area control (WAC)



- blue layer: interconnected generators
- fully decentralized control implemented locally
- distributed wide-area control using remote signals

Outline

inter-area oscillations

Dominant electro-mechanical swing dynamics

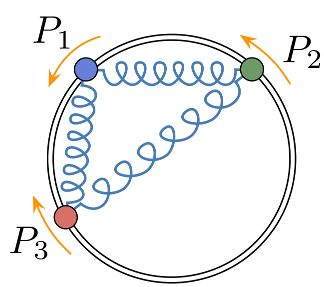
coarse-grained power network = coupled, forced, & heterogeneous pendula

generator **swing equations**:

$$M_i\ddot{\theta}_i + D_i\dot{\theta}_i = P_i - \sum_j B_{ij}\sin(\theta_i - \theta_j)$$

linearized at equilibrium $(\theta^*, \dot{\theta}^*, P^*)$:

$$M\ddot{\theta} + D\dot{\theta} + L\theta = P$$



where M, D are diagonal inertia and damping matrices & L is a Laplacian:

$$L = \begin{bmatrix} \vdots & \ddots & \vdots & \iddots & \vdots \\ -B_{i1}\cos(\theta_i^* - \theta_1^*) & \cdots & \sum_{j=1}^{n} B_{ij}\cos(\theta_i^* - \theta_j^*) & \cdots & -B_{in}\cos(\theta_i^* - \theta_n^*) \\ \vdots & \iddots & \vdots & \ddots & \vdots \end{bmatrix}$$

The main controllers to dampen oscillations

Automatic Voltage Regulator (AVR)

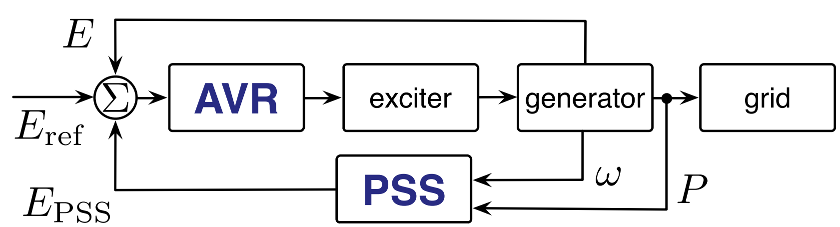
- objective: voltage = *const*.

$\Rightarrow$ diminishing damping

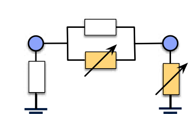
Power System Stabilizer (PSS)

- objective: net damping > 0

$\Rightarrow$ damping of oscillations



HVDC (high voltage DC) & **FACTS** (flexible AC transmission systems): control by modulating lines

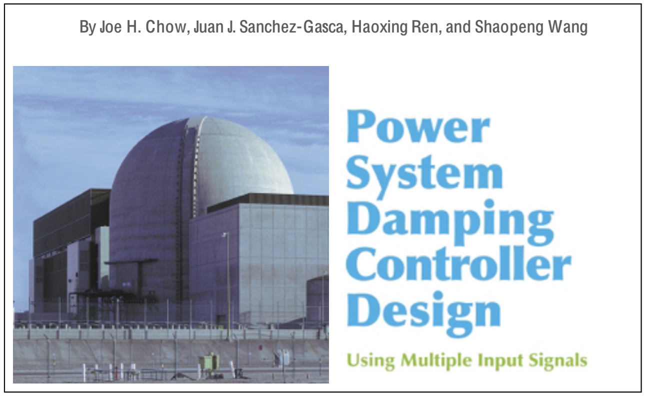


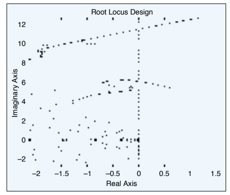
Control-induced oscillations

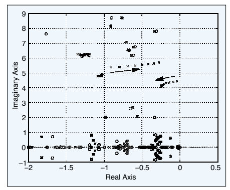
fact: multi-machine power systems have unstable zeros

⇒ multiple local controllers interact in an adverse way

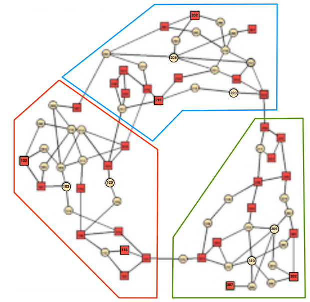
⇒ numerous tuning rules & heuristics for PSS design



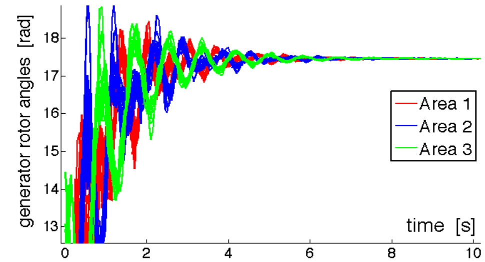




Inter-area oscillations in power networks



RTS 96 power network



swing dynamics

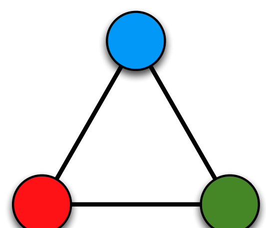
Groups of generators oscillate relative to each other due to ...

1. **heterogeneity** in responses (inertia M_i and damping D_i)
2. **topology**: modular & clustered
3. **power transfers** between areas: $a_{ij} = B_{ij} \cos(\theta_i^* - \theta_j^*)$
4. **interaction** of multiple local controllers

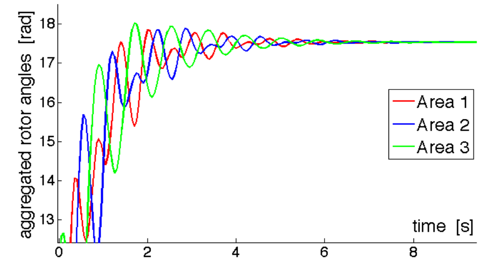
slow coherency modeling

with D. Romeres & F. Bullo

Slow coherency and area aggregation



aggregated RTS 96 model

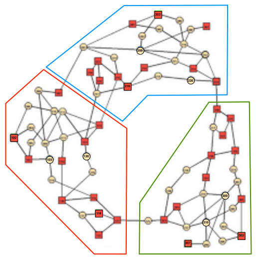


swing dynamics of aggregated model

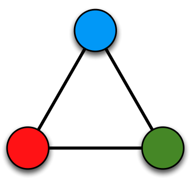
Aggregate model of lower dimension & with less complexity for

1. **analysis** and insights into inter-area dynamics [Chow & Kokotovic '85]
2. measurement-based **id** of equivalenced models [Chakrabortty et.al.'10]
3. **design** of remedial actions [Xu et. al. '11] & wide-area control (later)

Setup in slow coherency



original model



aggregated model

- r given **areas** (spectral partition [Chow et al. '85])
- parameter capturing **modularity/clustering**:
$$\delta = \frac{\max_\alpha(\Sigma \text{ external connections in area } \alpha)}{\min_\alpha(\Sigma \text{ internal connections in area } \alpha)}$$
- **inter-area dynamics** by center of inertia:
$$y_\alpha = \frac{\sum_{i\in\alpha} M_i\theta_i}{\sum_{i\in\alpha} M_i}\,, \quad \alpha \in \{1,\dots,r\}$$
- **intra-area dynamics** by area differences:
$$z^\alpha_{i-1} = \theta_i - \theta_1\,, \quad i \in \alpha\setminus\{1\},\ \alpha\in\{1,\dots,r\}$$

Linear transformation & time-scale separation

swing equation $\overset{T}{\underset{T^{-1}}{\Longleftrightarrow}}$ singular perturbation standard form

$$M\ddot\theta + D\dot\theta + L\theta = 0 \quad \overset{T}{\underset{T^{-1}}{\Longleftrightarrow}} \quad \left\{ \frac{d}{dt_s}\begin{bmatrix} y \\ \dot y \\ \sqrt{\delta}\,z \\ \sqrt{\delta}\,\dot z\end{bmatrix} = \begin{bmatrix} \ddots & \vdots & \iddots \\ \cdots & A & \cdots \\ \iddots & \vdots & \ddots \end{bmatrix}\begin{bmatrix} y \\ \dot y \\ z \\ \dot z\end{bmatrix}\right.$$

slow motion given by center of inertia:
$$y_\alpha = \frac{\sum_{i\in\alpha} M_i\theta_i}{\sum_{i\in\alpha} M_i}$$

fast motion given by intra-area differences:
$$z^\alpha_{i-1} = \theta_i - \theta_1$$

slow time scale: $t_s = \delta\cdot t\cdot$ "max internal area degree"

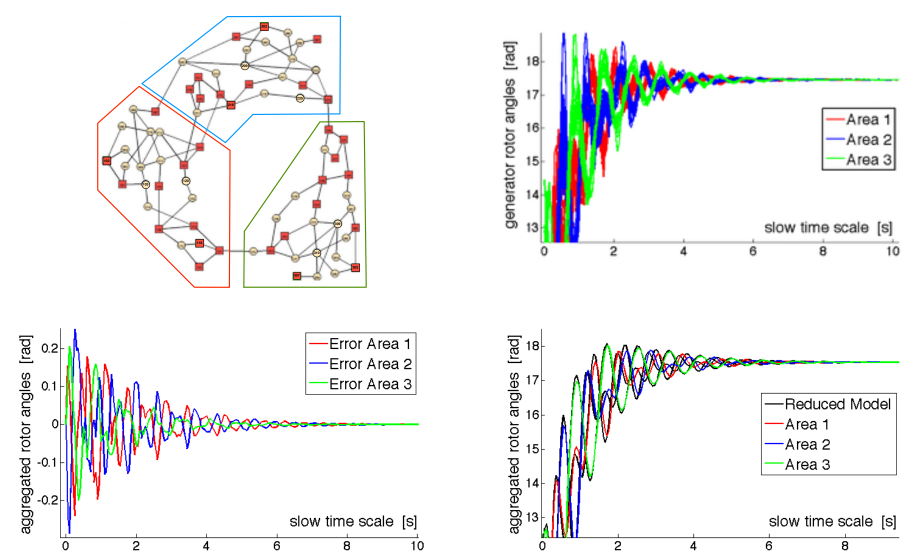
Area aggregation & approximation

- singular perturbation standard form:
$$\frac{d}{dt_s}\begin{bmatrix} y \\ \dot y \\ \sqrt{\delta}\,z \\ \sqrt{\delta}\,\dot z\end{bmatrix} = \begin{bmatrix} \ddots & \vdots & \iddots \\ \cdots & A & \cdots \\ \iddots & \vdots & \ddots \end{bmatrix}\begin{bmatrix} y \\ \dot y \\ z \\ \dot z\end{bmatrix}$$
- aggregated swing equations obtained by $\delta\downarrow 0$:
$$M_a\,\ddot\varphi + D_a\,\dot\varphi + L_{\text{red}}\,\varphi = 0$$

Properties of aggregated model [D. Romeres, FD, & F. Bullo, '13]

1. **inertia & damping:** $M_a = \begin{bmatrix}\ddots & & \\ & \sum_{i\in\alpha} M_i & \\ & & \ddots\end{bmatrix}$ & $D_a = \begin{bmatrix}\ddots & & \\ & \sum_{i\in\alpha} D_i & \\ & & \ddots\end{bmatrix}$
2. **Laplacian:** L_{red} = "inter-area" + "intra-area contributions"
 = positive semidefinite Laplacian with possibly negative weights
3. **approximation:** $\exists\,\delta^*$ such that for all $\delta\le\delta^*$: $y(t_s) = \varphi(t_s) + \mathcal{O}(\sqrt{\delta})$

RTS 96 swing dynamics revisited



conventional analysis

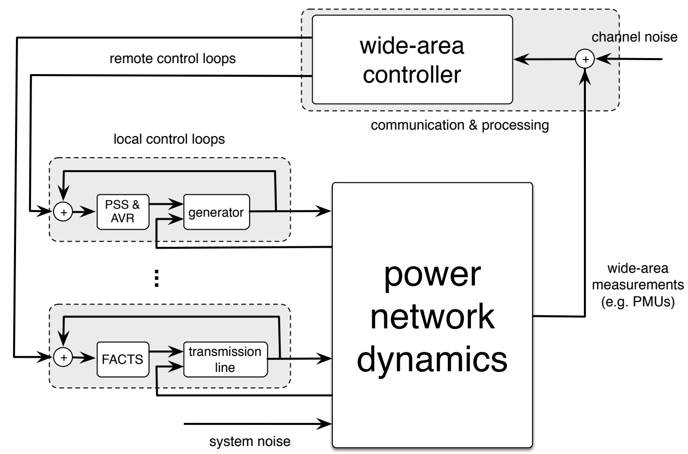
& wide-area control

(based on spectral methods)

I will be a little provocative ...

Canonical setup in wide-area control

local actuators, remote measurements, & communication backbone

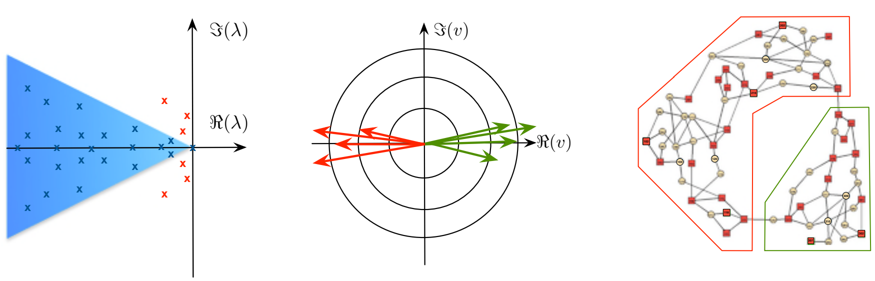


⇒ **problem I:** signal selection (sensors & actuators)

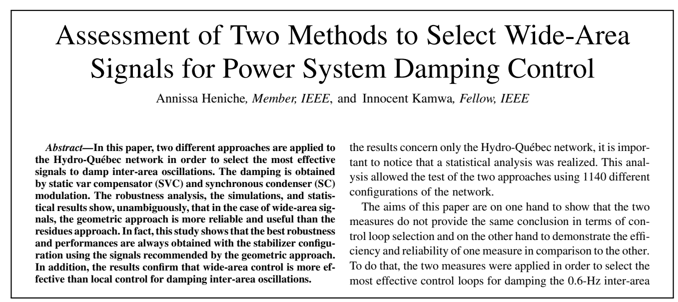
⇒ **problem II:** WAC design (subject to control signals)

Spectral analysis reveals the critical modes & areas

1. recall solution of $\dot{x} = Ax$: $x(t) = \sum_i \underbrace{v_i e^{\lambda_i t}}_{\text{mode } \#i} \cdot \underbrace{w_i^T x_0}_{\text{contribution from } x_0}$
2. analyze eigenvectors & participation factors of weakly damped modes
3. spectral partitioning reveals coherent groups in eigenvectors polarities



Modal signal selection metrics



Assessment of Two Methods to Select Wide-Area Signals for Power System Damping Control

Annissa Heniche, *Member, IEEE*, and Innocent Kamwa, *Fellow, IEEE*

***Abstract*—In this paper, two different approaches are applied to the Hydro-Québec network in order to select the most effective signals to damp inter-area oscillations. The damping is obtained by static var compensator (SVC) and synchronous condenser (SC) modulation. The robustness analysis, the simulations, and statistical results show, unambiguously, that in the case of wide-area signals, the geometric approach is more reliable and useful than the residues approach. In fact, this study shows that the best robustness and performances are always obtained with the stabilizer configuration using the signals recommended by the geometric approach. In addition, the results confirm that wide-area control is more effective than local control for damping inter-area oscillations.**

the results concern only the Hydro-Québec network, it is important to notice that a statistical analysis was realized. This analysis allowed the test of the two approaches using 1140 different configurations of the network.

The aims of this paper are on one hand to show that the two measures do not provide the same conclusion in terms of control loop selection and on the other hand to demonstrate the efficiency and reliability of one measure in comparison to the other. To do that, the two measures were applied in order to select the most effective control loops for damping the 0.6-Hz inter-area

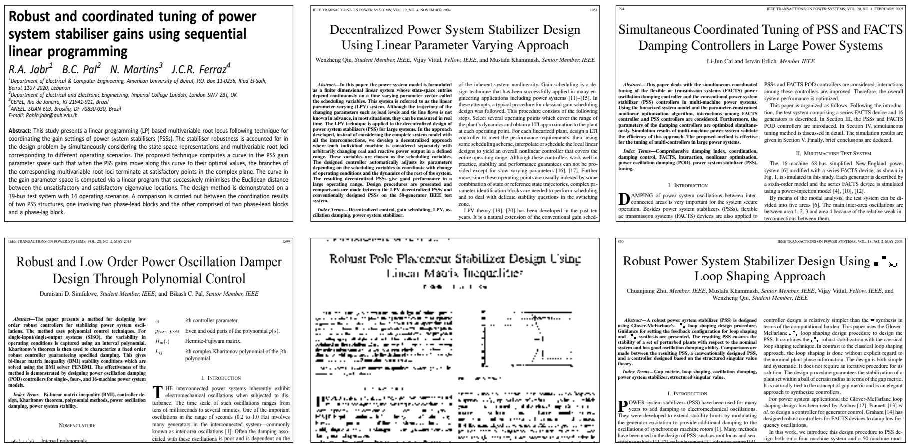
1. **geometric criteria** [H.M.A. Hamdan & A.M.A. Hamdan '87]:
   - modal controllability: effect of control input $\#j$ on mode $\#i$
   - modal observability: effect of control mode $\#i$ on sensor $\#j$
2. **frequency criteria** [M. Tarokh '92]: modal residues of transfer function

⇒ **suboptimal** procedures & many **requirements:** (i) identification of critical modes, (ii) sensor/actuator catalog, & (iii) combinatorial evaluation

Decentralized WAC control design

- ...subject to structural constraints is **tough**

$\Rightarrow$ ...usually handled with **suboptimal heuristics** in MIMO case


Robust and coordinated tuning of power system stabiliser gains using sequential linear programming

R.A. Jabr[1] B.C. Pal[2] N. Martins[3] J.C.R. Ferraz[4]

Decentralized Power System Stabilizer Design Using Linear Parameter Varying Approach

Simultaneous Coordinated Tuning of PSS and FACTS Damping Controllers in Large Power Systems

Robust and Low Order Power Oscillation Damper Design Through Polynomial Control

Robust Pole Placement Stabilizer Design Using Linear Matrix Inequalities

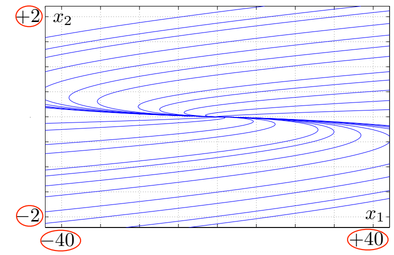
Robust Power System Stabilizer Design Using Loop Shaping Approach

Challenges in wide-area control

1. **signal selection** is combinatorial
2. **control design** is suboptimal
3. **identification** of critical modes is somewhat *ad hoc*

what information do you want to extract from the spectrum of a non-normal matrix?

Example: $\dot{x} = \begin{bmatrix} -1 & 10^2 \\ 0 & -1 \end{bmatrix} x$



Today:

$\Rightarrow$ performance metric: variance amplification of stochastic system

$\Rightarrow$ simultaneously optimize performance & control architecture

$\Rightarrow$ fully decentralized & nearly optimal controller

variance amplification as performance metric

with X. Wu & M. Jovanović

Input-output analysis in $\mathcal{H}_2$ - metric

- ...complementing/improving modal analysis
- ...same metric used later for control synthesis

- linear system with **white noise input**: $\dot{x} = Ax + B_1\eta$
- energy of homogeneous network as **performance output**: $z = Q^{1/2}x$
- **power spectral density** quantified by Hilbert-Schmidt norm

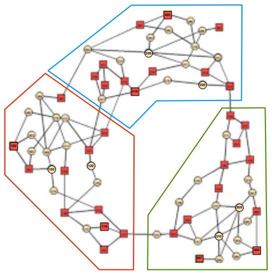
$$\|G(\mathrm{j}\,\omega)\|_{\mathrm{HS}}^2 \;=\; \mathrm{trace}\,(G(\mathrm{j}\,\omega)\cdot G^*(\mathrm{j}\,\omega)) \;=\; \sum_i \sigma_i^2(G(\mathrm{j}\,\omega))$$

- **steady-state variance** of the output quantified by $\mathcal{H}_2$-norm

$$\|G\|_{\mathcal{H}_2}^2 \;:=\; \lim_{t\to\infty} \mathbb{E}\left(x(t)^T\,Q\,x(t)\right) \;=\; \frac{1}{2\pi}\int_{-\infty}^{\infty}\|G(\mathrm{j}\,\omega)\|_{\mathrm{HS}}^2\,\mathrm{d}\omega$$

Slow coherency performance objectives

- recall **sources** for inter-area oscillations:



- linearized **swing equation**: $M\ddot{\theta} + D\dot{\theta} + L\theta = P$
- **mechanical energy**: $\frac{1}{2}\,\dot{\theta}M\dot{\theta} + \frac{1}{2}\,\theta^T L\theta$
- **heterogeneities** in topology, power transfers, & machine responses (inertia & damp)

$\Rightarrow$ performance **objectives** = energy of homogeneous network:

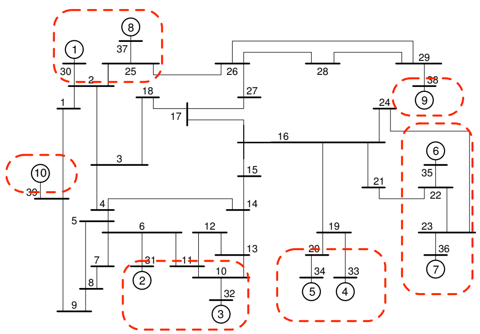
$$x^T Q\, x \;=\; \dot{\theta}^T M \dot{\theta} \;+\; \theta^T \left(I_n - (1/n) \cdot \mathbb{1}_{n\times n}\right)\theta$$

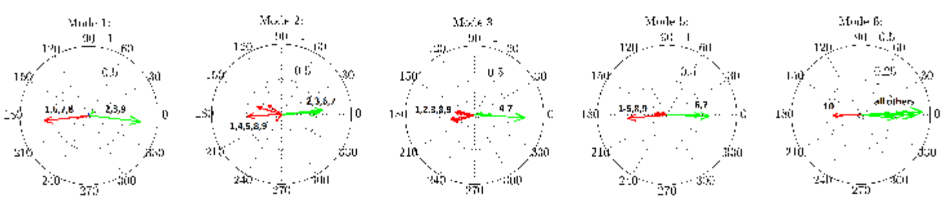
- other choices possible: center of inertia, inter-area differences, etc.

running case study: IEEE 39 New England Grid

Case study: IEEE 39 New England power grid

- **model features** (75 states):
  - sub-transient generator models [Athay et. al. '79]
  - open loop is unstable
  - exciters & tuned PSSs
- frequency & damping ratios of dominant **inter-area modes**

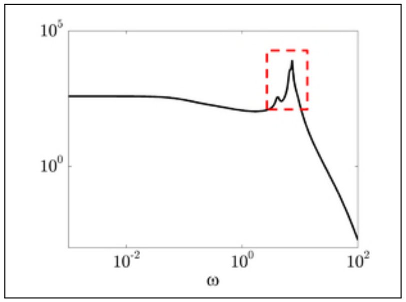


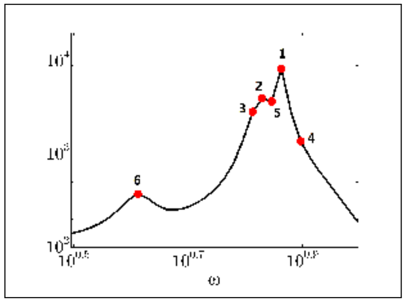


1.2Hz @ 1.2% 1.1Hz @ 2.6% 1.0Hz @ 3.7% 1.1Hz @ 6.8% 0.7Hz @ 7.8%

Power spectral density

...reveals inter-area modes & local mode # 4

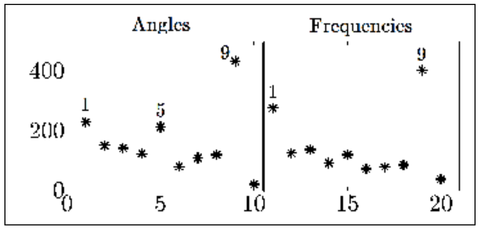




Variance amplification

via diagonal elements of output covariance matrix

...reveal #1 & #9 as crucial



sparsity-promoting optimal control

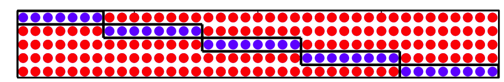
by F. Lin, M. Fardad, & M. Jovanović

Optimal linear quadratic regulator (LQR)

- **model:** linearized ODE dynamics $\dot{x}(t) = Ax(t) + B_1\eta(t) + B_2u(t)$
- **control:** memoryless linear state feedback $u = -Kx(t)$
- **optimal centralized control** with quadratic $\mathcal{H}_2$ - performance index:

$$\begin{array}{rl} \text{minimize} & J(K) \triangleq \lim_{t\to\infty} \mathbb{E}\left\{x(t)^T Q x(t) + u(t)^T R u(t)\right\} \\ \text{subject to} & \\ \text{linear dynamics:} & \dot{x}(t) = Ax(t) + B_1\eta(t) + B_2u(t), \\ \text{linear control:} & u(t) = -Kx(t), \\ \text{stability:} & (A - B_2K) \text{ Hurwitz.} \end{array}$$

(no structural constraints on K)



Sparsity-promoting optimal LQR

[Lin, Fardad, & Jovanović '13]

simultaneously optimize performance & architecture

$$\begin{array}{rl} \text{minimize} & \lim_{t\to\infty} \mathbb{E}\left\{x(t)^T Q x(t) + u(t)^T R u(t)\right\} + \gamma\, \mathrm{card}(K) \\ \text{subject to} & \\ \text{linear dynamics:} & \dot{x}(t) = Ax(t) + B_1\eta(t) + B_2u(t), \\ \text{linear control:} & u(t) = -Kx(t), \\ \text{stability:} & (A - B_2K) \text{ Hurwitz.} \end{array}$$

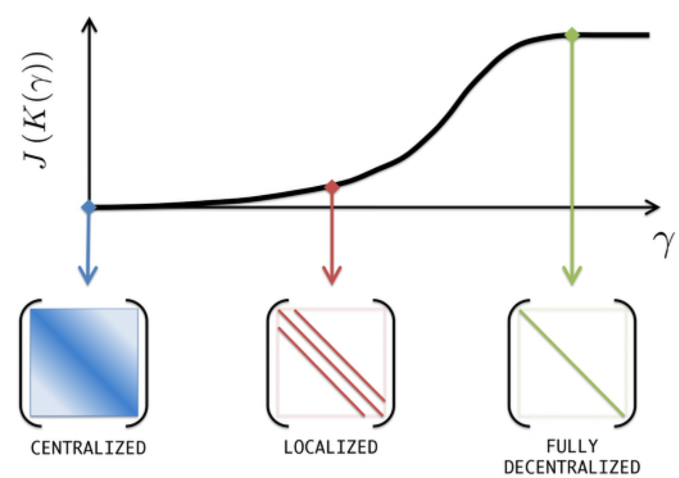
$\Rightarrow$ for $\gamma = 0$: standard optimal control (typically not sparse)

$\Rightarrow$ for $\gamma > 0$: sparsity is promoted (problem is combinatorial)

$\Rightarrow$ $\mathrm{card}(K)$ convexified by weighted ℓ_1-norm $\sum_{i,j} w_{ij}|K_{ij}|$

Parameterized family of feedback gains

$$K(\gamma) = \arg\min_K \left(J(K) + \gamma \cdot \sum_{i,j} w_{ij}|K_{ij}|\right)$$



Algorithmic approach to sparsity-promoting control

1. equivalent formulation via **observability Gramian** P:

$$\begin{aligned} \text{minimize} \quad & J_\gamma(K) \triangleq \text{trace}\left(B_1^T P B_1\right) + \gamma \cdot \sum\nolimits_{i,j} w_{ij} \, |K_{ij}| \\ \text{subject to} \quad & (A - B_2 K)^T P + P(A - B_2 K) \\ & \qquad = -(Q + K^T R K) \end{aligned}$$

2. **warm-start** at optimal centralized $\mathcal{H}_2$ - controller with $\gamma = 0$
3. **homotopy path:** continuously increase γ until the desired value γ_{des}
4. **ADMM:** iterative solution for each value of $\gamma \in [0, \gamma_{\text{des}}]$
5. **update weights:** update w_{ij} in each ADMM step: $w_{ij} \mapsto \frac{1}{|K_{ij}| + \varepsilon}$
6. **polishing:** structured optimization with desired sparsity pattern

Some ADMM details

0. minimize $f(K) + \gamma \cdot g(K) \; = \; \mathcal{H}_2$ - performance $+ \; \gamma \cdot$ sparsity
1. additional variable/constraint decoupling smooth & separable objectives:

$$\begin{aligned} \text{minimize} \quad & f(K) + \gamma \cdot g(L) \\ \text{subject to} \quad & K - L = 0 \end{aligned}$$

2. introduce augmented Lagrangian

$$\mathcal{L}_\rho(K, L, \Lambda) = f(K) + \gamma \cdot g(L) + \text{trace}(\Lambda(K - L)) + \frac{\rho}{2} \|K - L\|_F^2$$

3. alternating direction method of multipliers (ADMM):

$$\begin{aligned} K^+ &\triangleq \text{argmin}_K \, \mathcal{L}_\rho(K, L, \Lambda) && \text{(iteratively via smooth method)} \\ L^+ &\triangleq \text{argmin}_L \, \mathcal{L}_\rho(K^+, L, \Lambda) && \text{(analytically via soft-thresholding)} \\ \Lambda^+ &\triangleq \Lambda + \rho \cdot (K^+ - L^+) \end{aligned}$$

$\Rightarrow$ **guarantees:** stabilizing gains (always) & convergent (if locally convex)

sparsity-promoting control of inter-area oscillations

with M. Jovanović, M. Chertkov, & F. Bullo

Regularization of rotational symmetry

- **rotational symmetry** of power flow (absence of reference angle)

$$M_i \ddot{\theta}_i + D_i \dot{\theta}_i = P_i - \sum\nolimits_j B_{ij} \sin(\theta_i - \theta_j)$$

$\Rightarrow$ $[\theta \;\, r] = [\mathbb{1}_n \;\, \mathbb{O}]$ is eigenvector of linearized power system models

$\Rightarrow$ eigenvector is not detectable: $[\mathbb{1}_n \;\, \mathbb{O}]^T \, Q \, [\mathbb{1}_n \;\, \mathbb{O}] = 0$

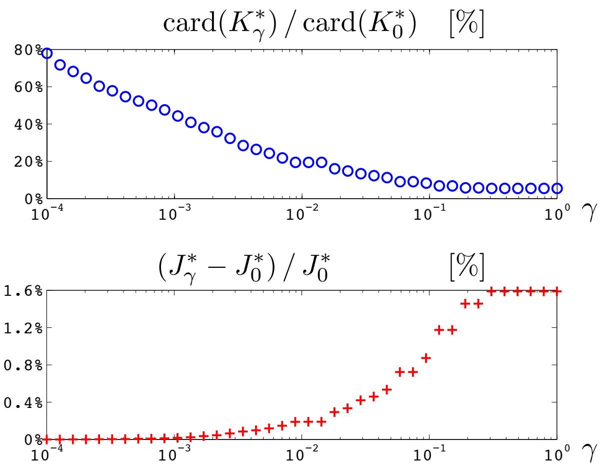
$\Rightarrow$ **no numeric LQR solution** with standard Ricatti solvers

- **regularization:** $x^T Q \, x \; = \; \dot{\theta}^T M \dot{\theta} \; + \; \theta^T \left((1 + \varepsilon) I_n - (1/n) \cdot \mathbb{1}_{n \times n}\right) \theta$

$\Rightarrow$ resulting feedback requires **absolute angle**: $K_\varepsilon \, [\mathbb{1}_n \;\, \mathbb{O}] = \varepsilon \cdot [\star \;\; \mathbb{O}]$

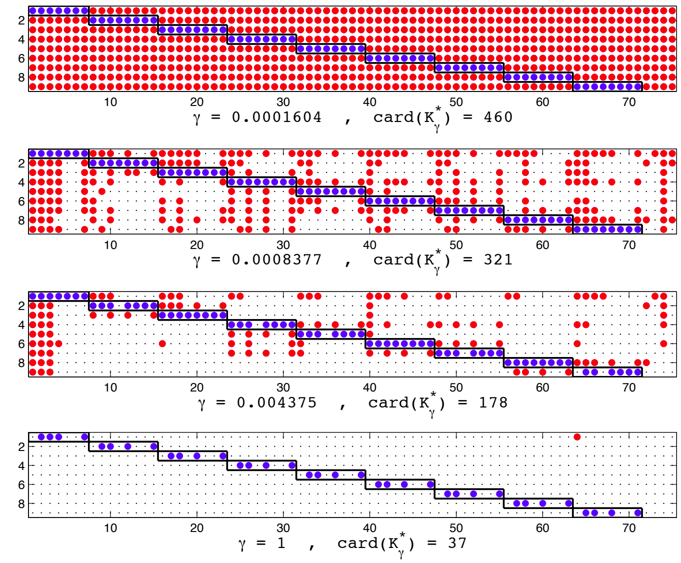
Performance vs. sparsity

Q = energy of homogeneous network , $R = I_n$, $\gamma \in [10^{-4}, 10^{0}]$



for $\gamma = 1 \Longrightarrow \begin{cases} 1.6\,\% & \text{relative performance loss} \\ 5.5\,\% & \text{non-zero elements in } K \end{cases}$

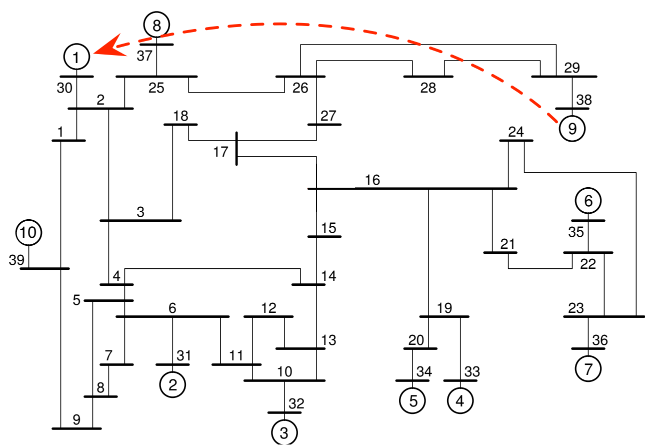
Control architecture & signal exchange network



For $\gamma = 1$: local decentralized optimal control $+$ $K_{19}^* \, \theta_9(t)$

Sparse & nearly optimal wide-area control architecture

single wide-area control link $\Longrightarrow$ nearly centralized performance



caveat: ε-regularization results in feedback requiring the absolute angle θ_9

. . . but there is no absolute angle !

too much plain vanilla . . .

. . . need a closer look at

rotational symmetry

fully decentralized & optimal control

with X. Wu & M. Jovanović

Taking the rotational symmetry into account

- **structural constraint:** there is no absolute angle

$$\text{open-loop: } A \begin{bmatrix} \mathbb{1} \\ \mathbb{0} \end{bmatrix} = \begin{bmatrix} \mathbb{0} \\ \mathbb{0} \end{bmatrix} \implies \text{closed-loop: } (A - B_2 K) \begin{bmatrix} \mathbb{1} \\ \mathbb{0} \end{bmatrix} = \begin{bmatrix} \mathbb{0} \\ \mathbb{0} \end{bmatrix}$$

$\Rightarrow$ **elimination** of the average mode $\mathbb{1}$

$$x = \begin{bmatrix} \theta \\ r \end{bmatrix} = \underbrace{\begin{bmatrix} U & 0 \\ 0 & I \end{bmatrix}}_{T} \xi + \begin{bmatrix} \mathbb{1} \\ 0 \end{bmatrix} \bar{\theta}$$

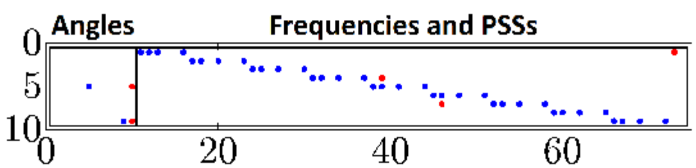
where U is orthonormal with columns $\perp$ span $(\mathbb{1})$

- **embedding in ADMM** to promote sparsity in original coordinates

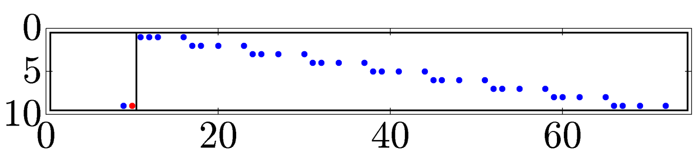
$$\text{minimize } f(K) + \gamma \cdot g(L) \qquad \text{subject to } K T^T - L = 0$$

Control architecture & signal exchange network

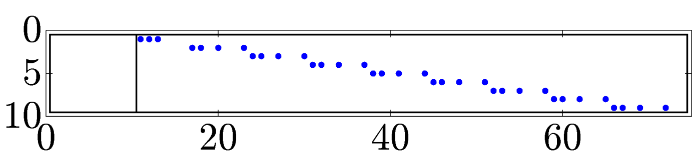
under symmetry considerations leads to fully decentralized control



$\gamma = 0.0818$, **card** $(K) = 43$



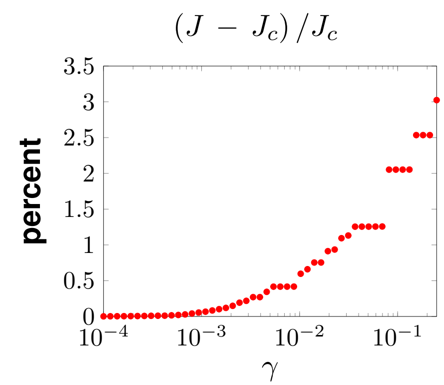
$\gamma = 0.1548$, **card** $(K) = 38$

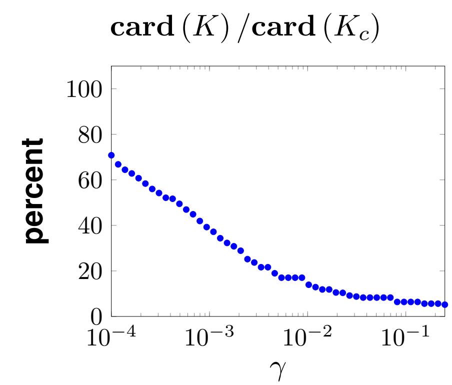


$\gamma = 0.2500$, **card** $(K) = 35$

Performance vs. sparsity

Q = energy of homogeneous network , $R = I_n$, $\gamma \in [10^{-4}, 0.25]$





$$\gamma = 0.25 \Rightarrow \begin{cases} 3.0\,\% & \text{relative performance loss} \\ 5.2\,\% & \text{non-zero elements in } K \end{cases}$$

$\Rightarrow$ fully decentralized control is nearly optimal !

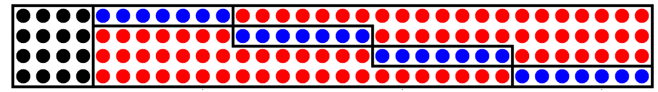
from a practical implementation perspective we should consider

block-sparsity

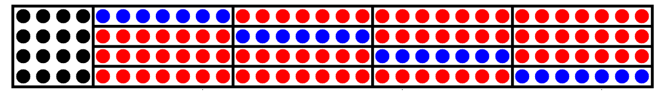
Extensions to block sparsity

$$\begin{array}{ll} \text{minimize} & J(F) \;+\; \gamma_\theta \cdot g_\theta(K_\theta) \;+\; \gamma_r \cdot g_r(K_r) \\ \text{subject to} & F\,T^T \;-\; \left[\; K_\theta \quad K_r \;\right] \;=\; 0 \end{array}$$

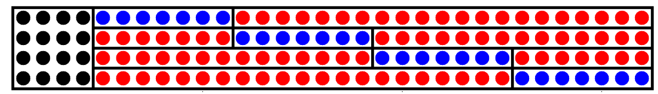
where $g_\theta(K_\theta) = \sum_{i,j} w_{ij}\,|K_{\theta\,ij}|$ & off-diagonal **block-regularizations** are



element-wise $g_r = \sum_{i,j} w_{ij}\,|\,(I_s \circ K_r)_{ij}\,|$



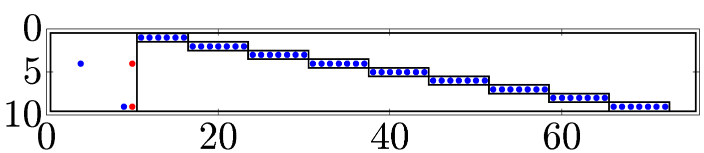
block-wise $g_r = \sum_{i \neq k} \beta_{ik}\, w_{ik}\, \|\, \mathrm{e}_i^T (I_s \circ K_r) \circ v_k^T \|_2$



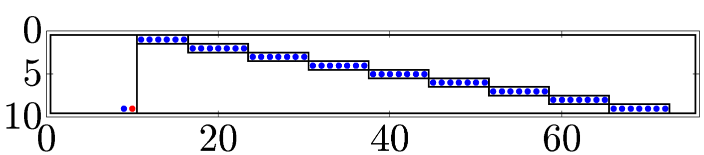
row-wise $g_r = \sum_i \beta_i\, w_i\, \|\, \mathrm{e}_i^T (I_s \circ K_r)\, \|_2$

Block-sparse control architecture

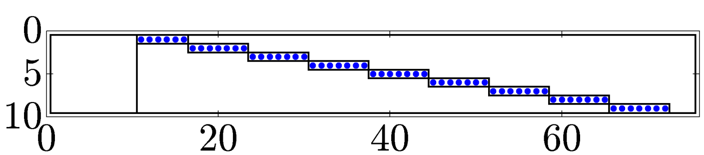
under symmetry considerations & block sparsity leads to fully decentralized control



$\gamma = 0.0697$, $\mathbf{card}\,(K) = 66$



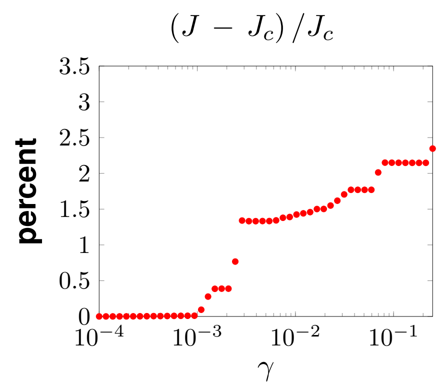
$\gamma = 0.0818$, $\mathbf{card}\,(K) = 64$

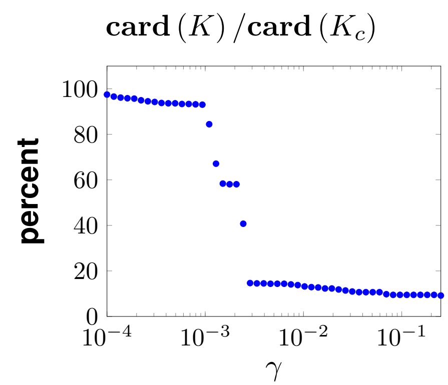


$\gamma = 0.2500$, $\mathbf{card}\,(K) = 62$

Performance vs. sparsity

Q = energy of homogeneous network , $R = I_n$, $\gamma \in [10^{-4}, 0.25]$

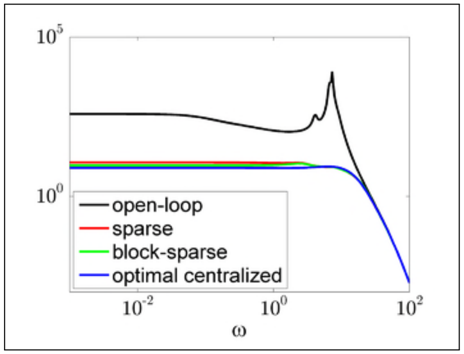




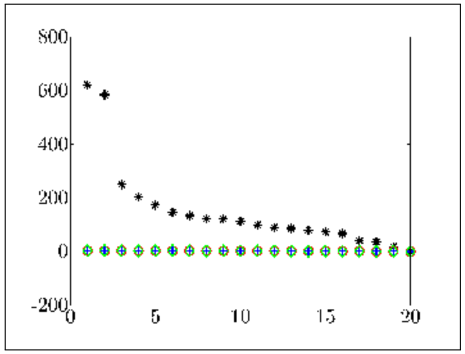
$$\gamma = 0.25 \;\Rightarrow\; \begin{cases} 2.3\,\% & \text{relative performance loss} \\ 9.2\,\% & \text{non-zero elements in } K \end{cases}$$

$\Rightarrow$ fully decentralized control is nearly optimal **!**

Performance of different approaches



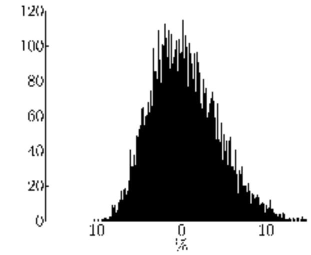
power spectral density



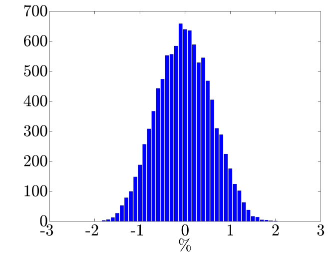
variance amplification

Robustness: optimal control reduces sensitivity

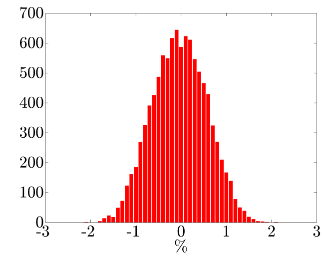
nominal controller applied to $10,000$ operating points with $\pm 20\%$ randomized loading



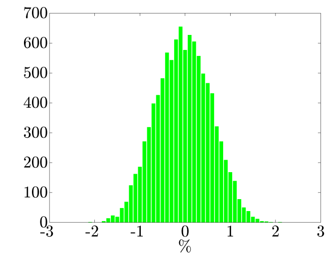
open-loop system



centralized controller

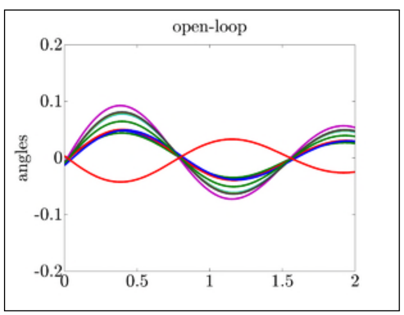


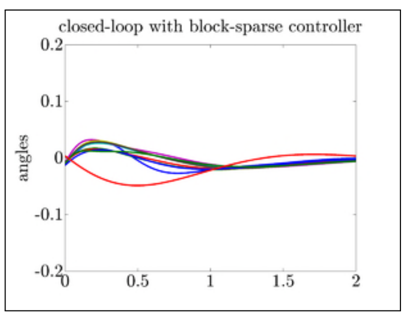
sparse controller

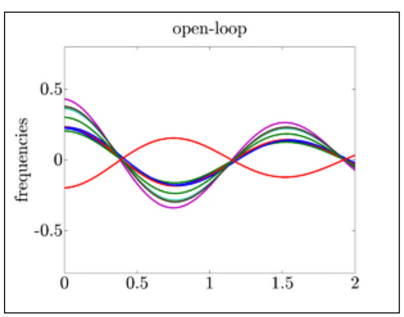


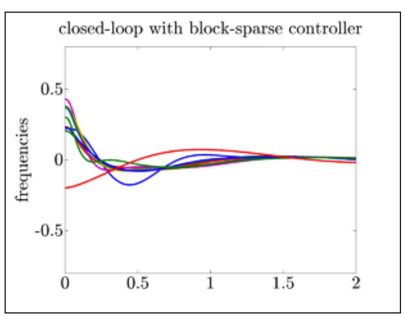
block-sparse controller

Eye candy: time-domain simulations









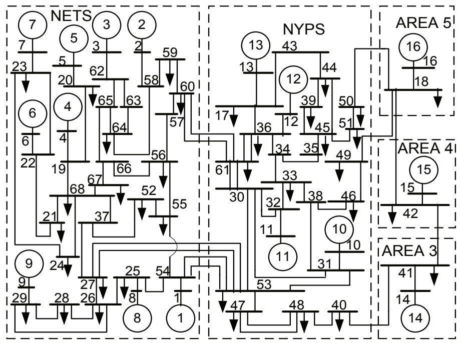
we can also go

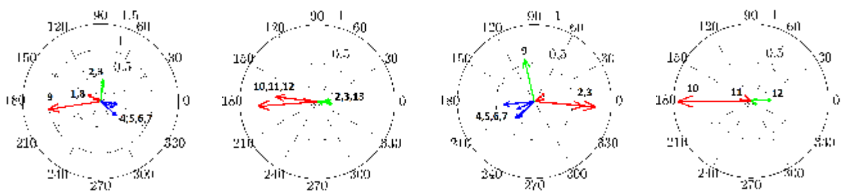
to larger setups

(seminar time permitting)

Case study: New England – New York test system

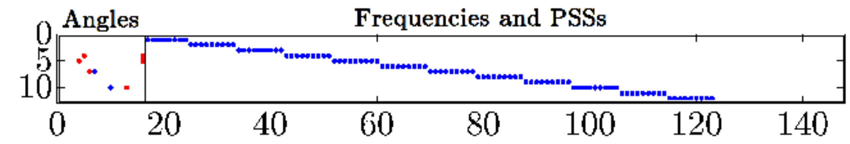
- **model features** (242 states):
  - sub-transient generator models [Singh et. al. '14]
  - open loop is unstable
  - exciters & tuned PSSs
- frequency & damping ratios of dominant **inter-area modes**



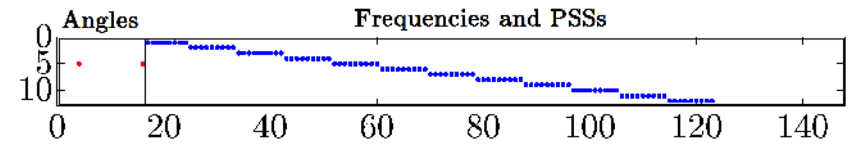


1.1Hz @ 3.8%   1.3Hz @ 4.2%   1.1Hz @ 4.7%   1.3Hz @ 4.9%

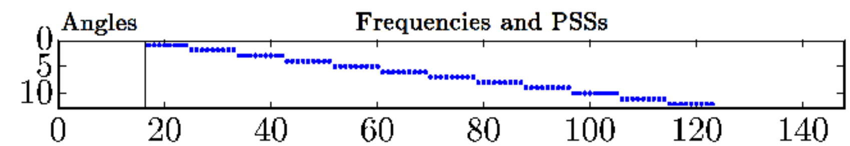
Block-sparse control architecture



$\gamma = 0.0429$, **card** $(K) = 115$



$\gamma = 0.0655$, **card** $(K) = 109$

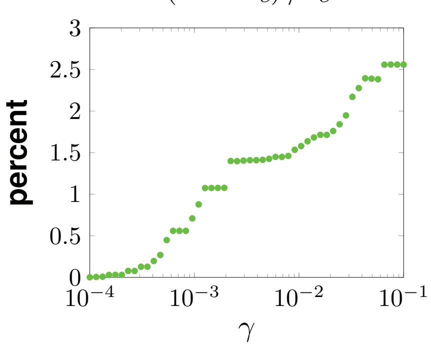


$\gamma = 0.1$, **card** $(K) = 107$

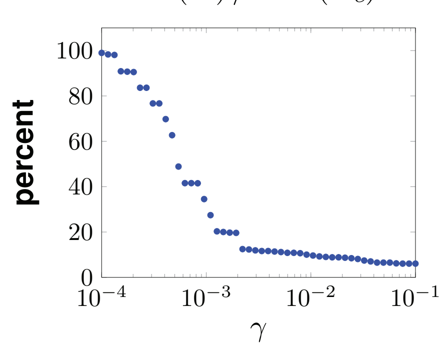
Performance vs. sparsity

Q = energy of homogeneous network , $R = I_n$, $\gamma \in [10^{-4}, 10^{-1}]$

$(J - J_c)/J_c$



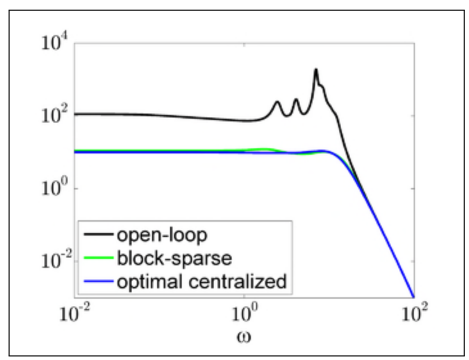
$\mathbf{card}\,(K)/\mathbf{card}\,(K_c)$



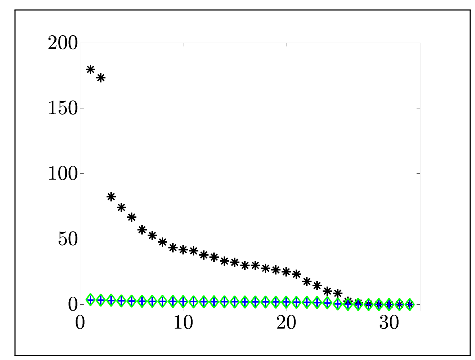
$$\gamma = 0.1 \Rightarrow \begin{cases} 2.6\,\% & \text{relative performance loss} \\ 6.1\,\% & \text{non-zero elements in } K \end{cases}$$

$\Rightarrow$ fully decentralized control is nearly optimal **!**

Performance of different approaches



power spectral density



variance amplification

Summary & conclusions

1. analysis of inter-area dynamics via slow coherency theory
2. sparsity-promoting distributed optimal wide-area control

⇒ trade-off: sparse control architecture vs. performance

3. extensions to rotational symmetry & block sparsity

⇒ yields fully decentralized & nearly optimal controllers

4. illustrations with New England & New York power grid models

Code available online

- sparsity-promoting wide-area control:
  `http://www.ece.umn.edu/users/mihailo/software/lqrsp/wac.html`
- extensions to rotational symmetry & block sparsity:
  `www.umn.edu/~mihailo/software/lqrsp/matlab-files/lqrsp_wac.zip`

Acknowledgements & main references

D. Romeres, F. Dörfler, and F. Bullo. Novel results on slow coherency in consensus and power networks. *European Control Conference*, July 2013.

F. Dörfler, M. Jovanović, Michael Chertkov, and F. Bullo. Sparsity-Promoting Optimal Wide-Area Control of Power Networks. *IEEE Transactions on Power Systems*, July 2014.

X. Wu, F. Dörfler, and M. Jovanović. Input-output analysis and decentralized optimal control of inter-area oscillations in power systems. Available at `http://arxiv.org`, February 2015.

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