Sparsity-promoting wide-area control of power systems

F. Dörfler, Mihailo Jovanović, M. Chertkov, and F. Bullo

2013 American Control Conference

Electro-mechanical oscillations in power systems

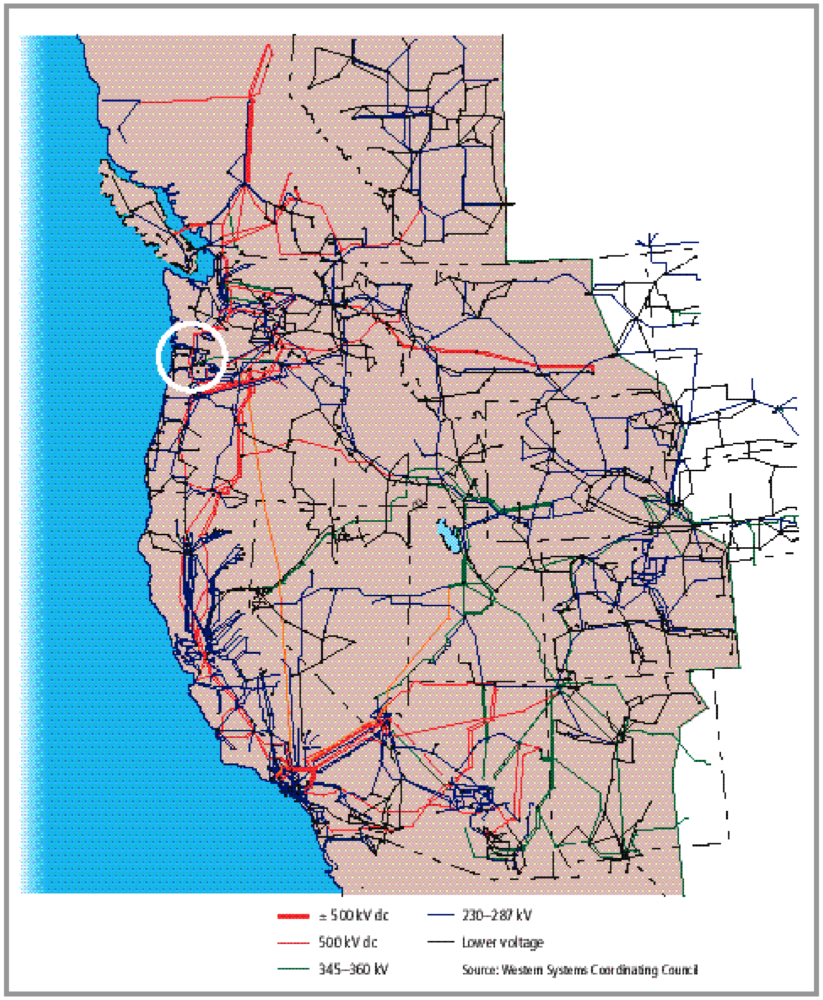
- **Local oscillations**
  - ⋆ single generators swing relative to the rest of the grid
  - ⋆ typically damped by Power System Stabilizers (PSSs)

- **Inter-area oscillations**
  - ⋆ groups of generators oscillate relative to each other
  - ⋆ associated with dynamics of power transfers

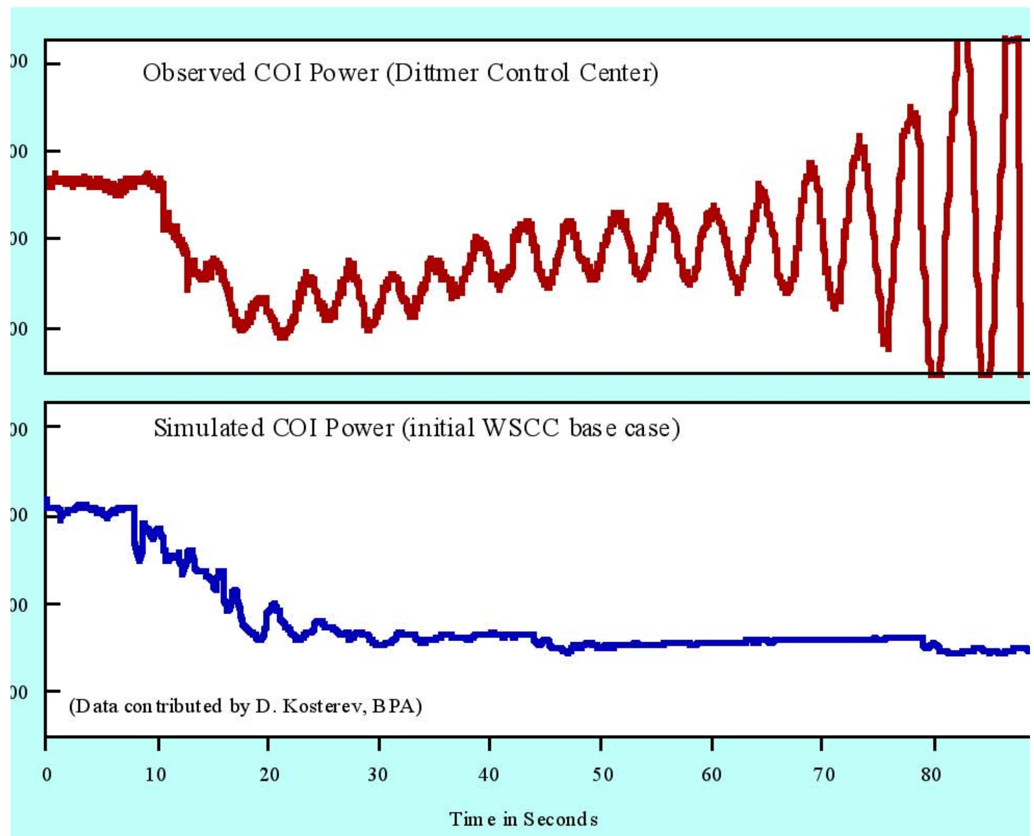
Inter-area oscillations

- **Blackout of Aug. 10, 1996**
  - ⋆ **resulted from instability of the $0.25\,\mathrm{Hz}$ mode**

western interconnected system:



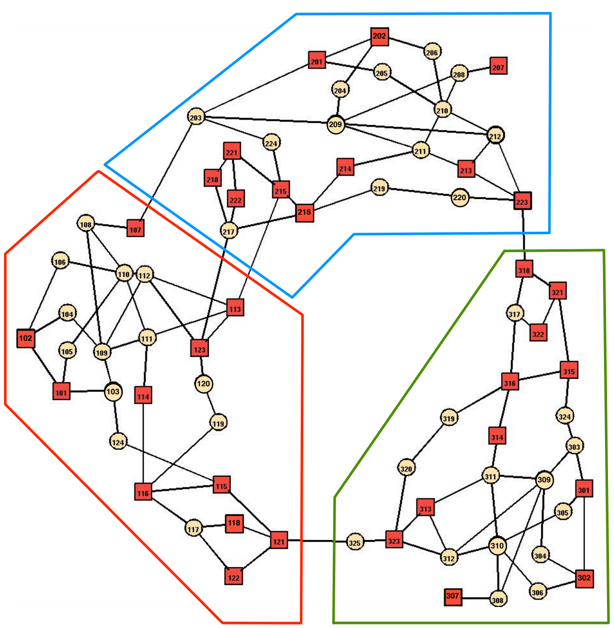
California-Oregon power transfer:



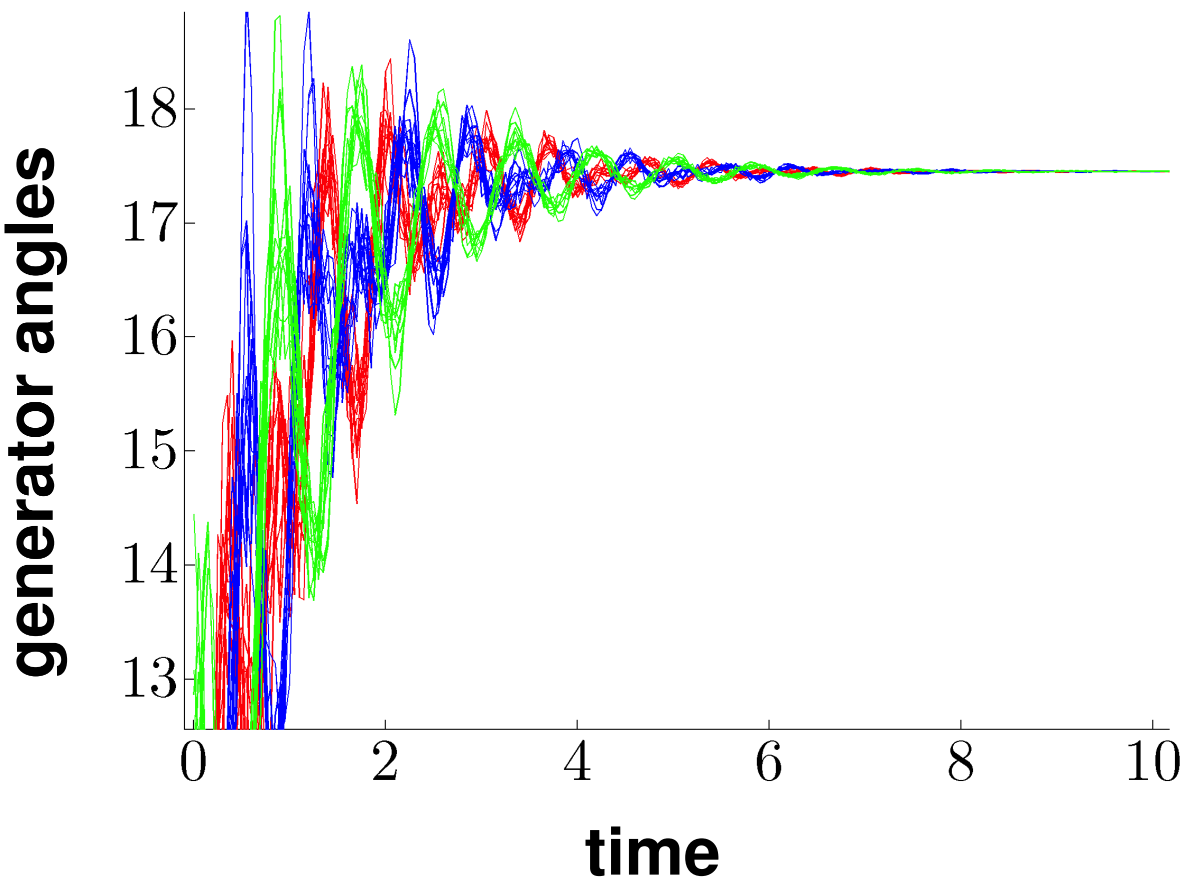
Slow coherency theory

- WHERE ARE THE INTER-AREA MODES COMING FROM?
  - ⋆ **slow coherency theory** *Chow, Kokotović, et al. ’78, ’82*

RTS 96 power system:

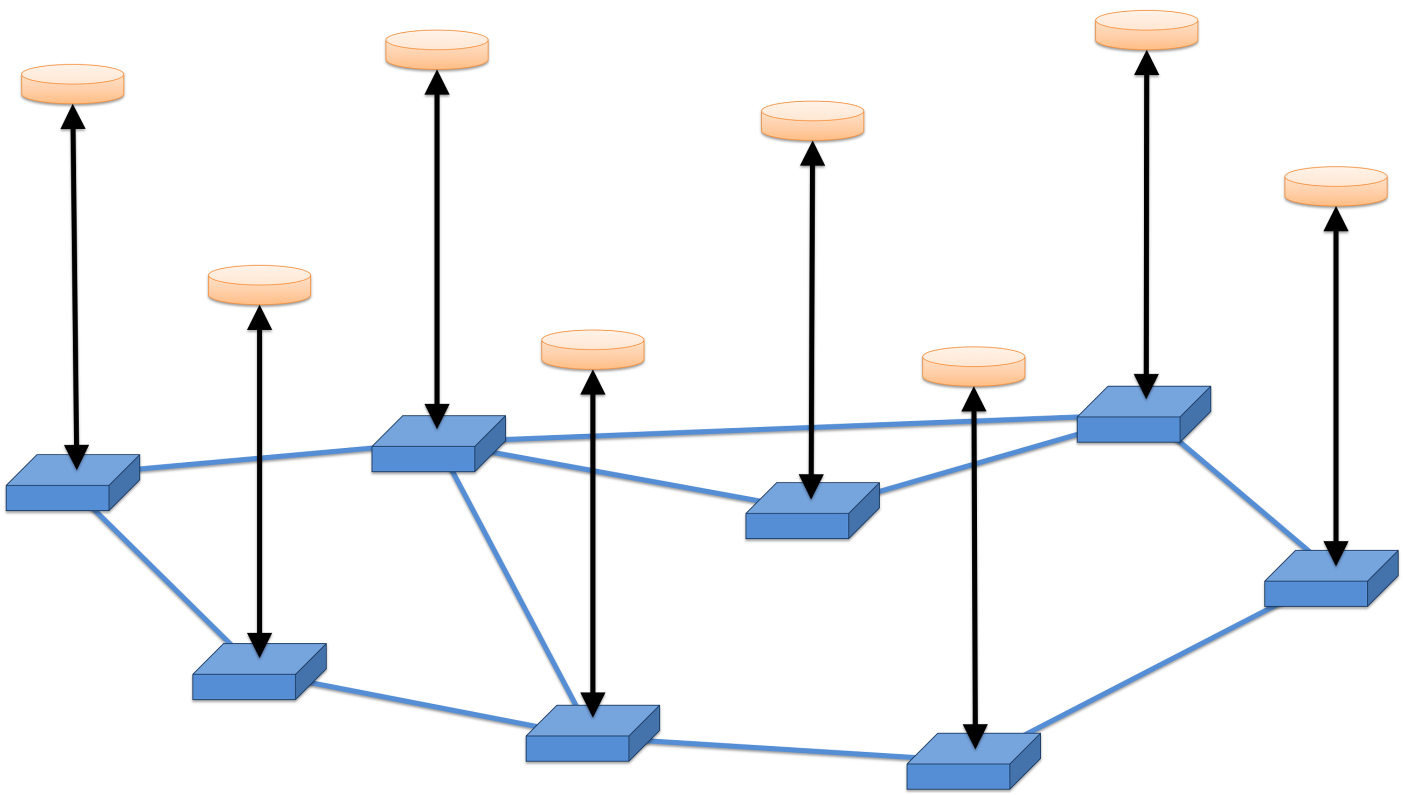


linearized swing equation:



Conventional control

- **Blue layer: generators with transmission lines**

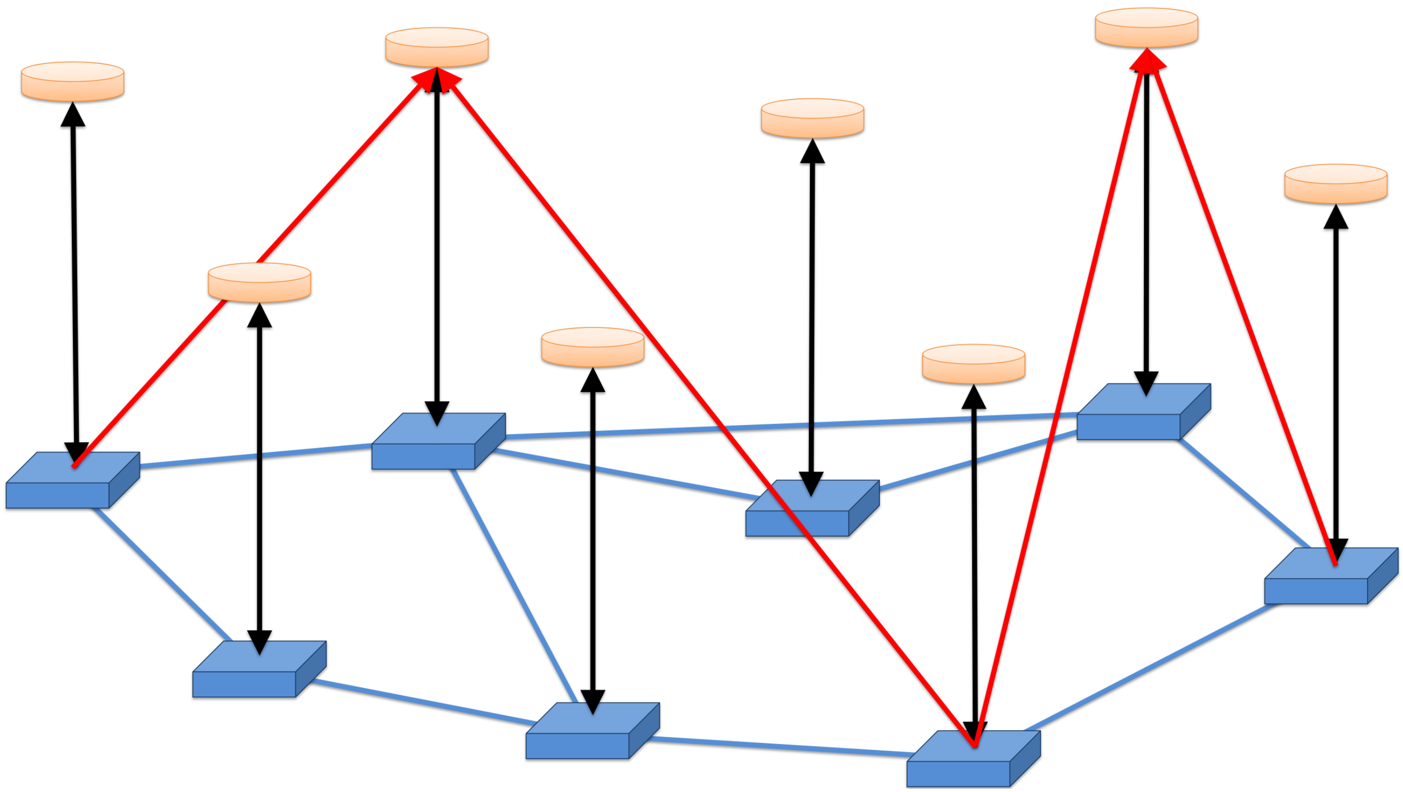


- **Fully decentralized controller**
  - ⋆ effective against local oscillations
  - ⋆ ineffective against inter-area oscillations

Wide-area control

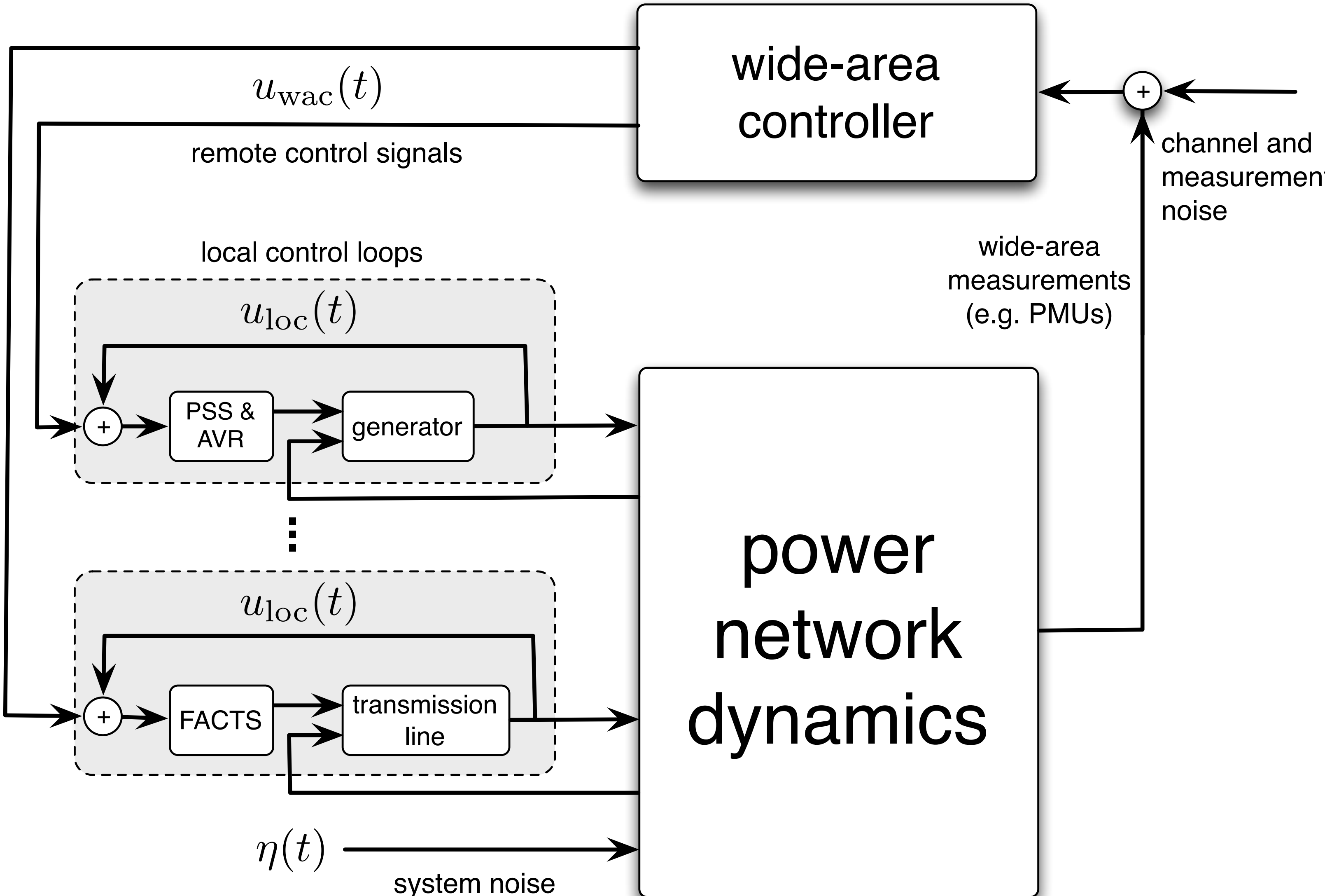
- **Blue layer: generators with transmission lines**

wide-area controller



KEY CHALLENGE:

identification of a signal exchange network
performance vs sparsity



wide-area controller
$u_{\mathrm{wac}}(t)$
remote control signals
channel and measurement noise
wide-area measurements (e.g. PMUs)
local control loops
$u_{\mathrm{loc}}(t)$
PSS & AVR
generator
$u_{\mathrm{loc}}(t)$
FACTS
transmission line
power network dynamics
$\eta(t)$
system noise

Outline

❶ SPARSITY-PROMOTING WIDE-AREA CONTROL

- ⋆ **Safeguard against inter-area oscillations**
- ⋆ **Performance vs sparsity**

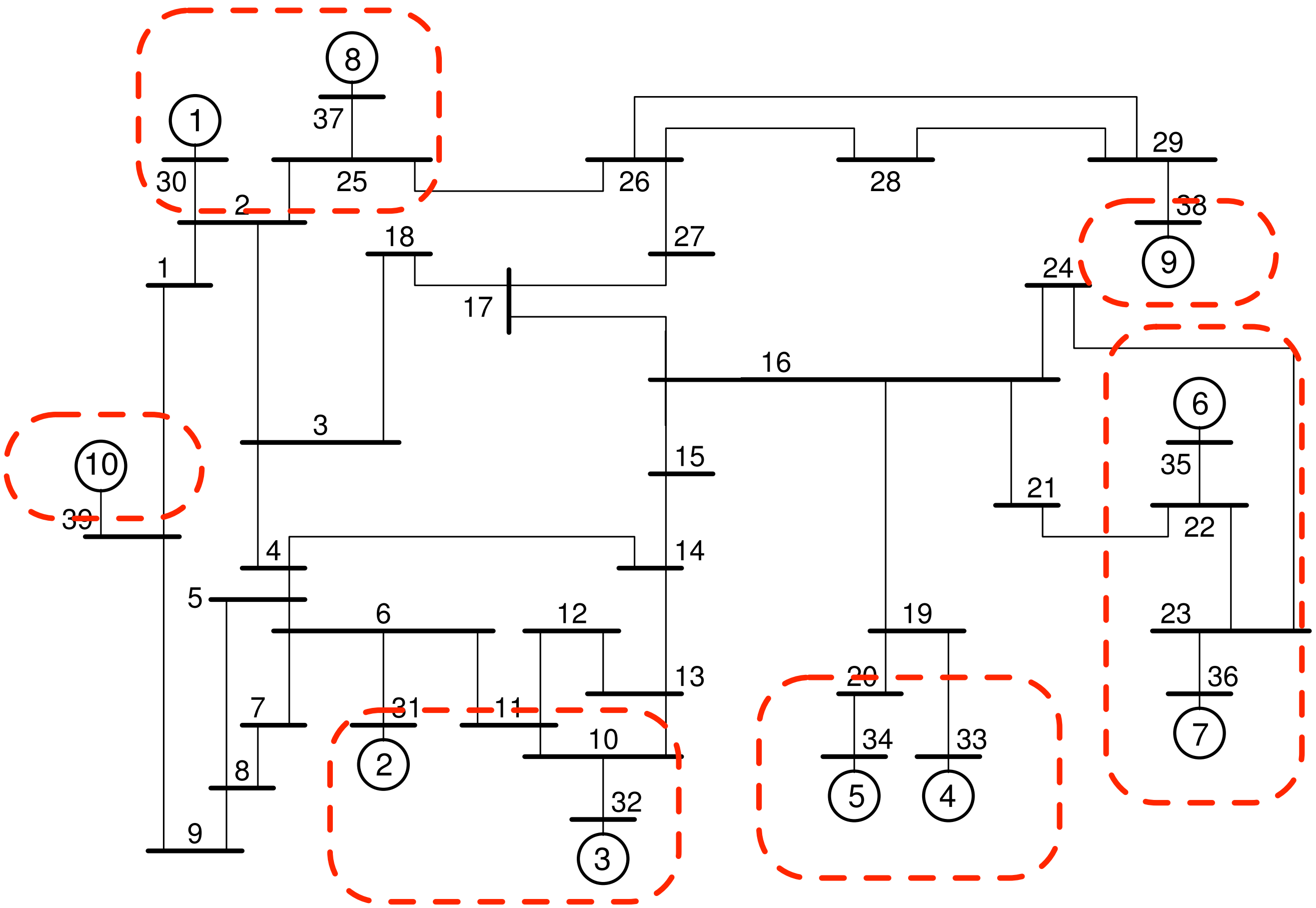
❷ CASE STUDY

- ⋆ **IEEE New England power grid model**

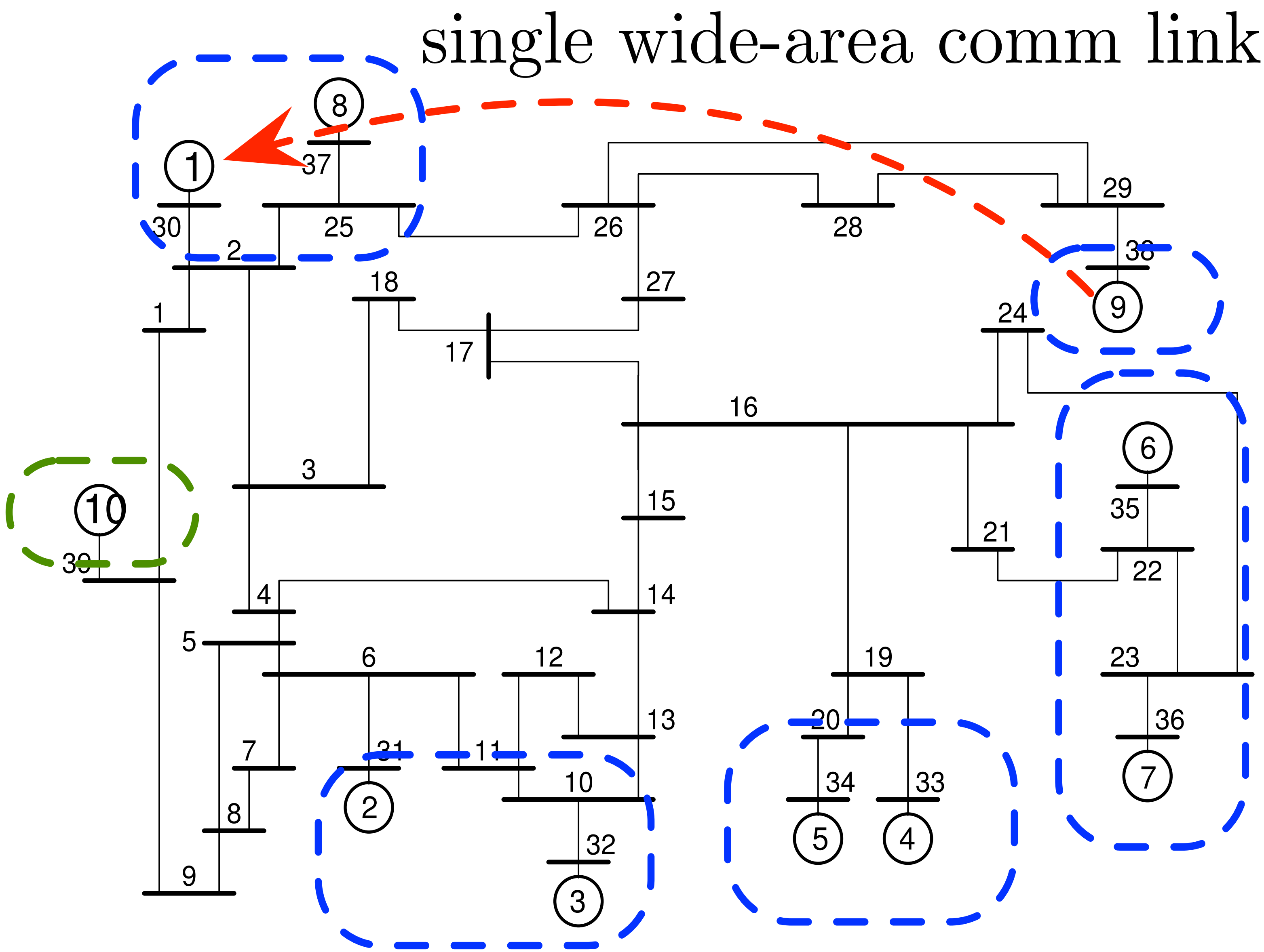
❸ SUMMARY AND OUTLOOK

Case study: IEEE New England Power Grid

- MODEL FEATURES
  - ⋆ detailed sub-transient generator models
  - ⋆ exciters
  - ⋆ carefully tuned PSS data



Preview of a key result



single long range interaction $\Rightarrow$ **nearly centralized performance**

Optimal wide-area control

linearized dynamics: $\dot{x} \;=\; A\,x \;+\; B_1\,d \;+\; B_2\,u$

objective function: $J \;=\; \lim_{t \,\to\, \infty} \mathcal{E}\left(x^T(t)\,Q\,x(t) \;+\; u^T(t)\,R\,u(t)\right)$

memoryless controller: $u \;=\; -K\,x$

⋆ **no structural constraints**

globally optimal controller:

$$\boxed{\begin{aligned} A^T P \;+\; P\,A \;-\; P\,B_2\,R^{-1}B_2^T P + Q \;&=\; 0 \\ K_c \;&=\; R^{-1}B_2^T P \end{aligned}}$$

Sparsity-promoting optimal control

$$\text{minimize} \quad \underbrace{J(K)}_{\text{variance amplification}} \quad + \quad \underbrace{\gamma \sum_{i,\,j} W_{ij}\,|K_{ij}|}_{\text{sparsity-promoting penalty function}}$$

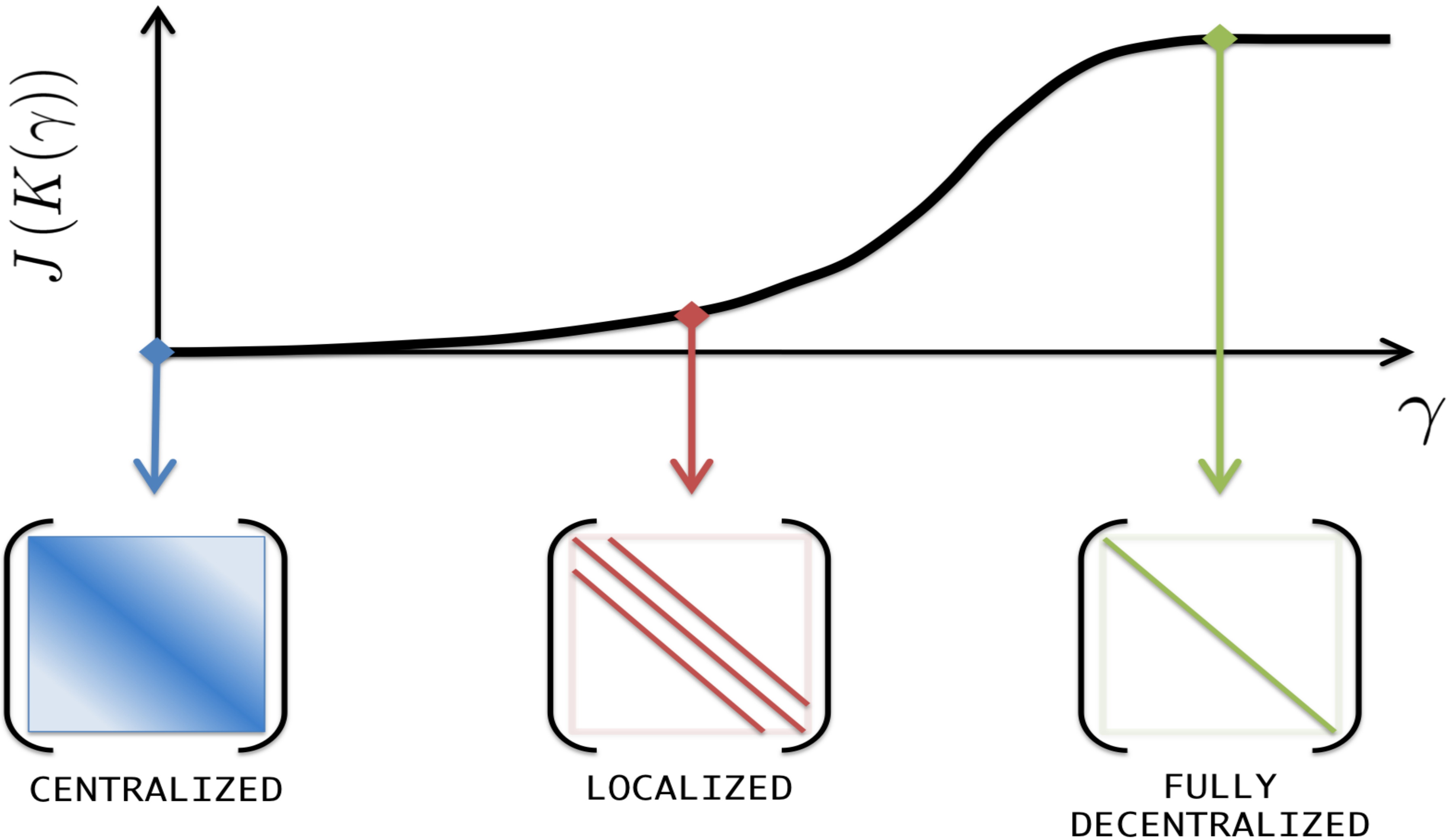
$\star\ \gamma > 0$ – performance vs sparsity tradeoff

$\star\ W_{ij} \geq 0$ – weights (for additional flexibility)

Lin, Fardad, Jovanović, IEEE TAC '13 (in press; arXiv:1111.6188)

Parameterized family of feedback gains

$$K(\gamma) \; := \; \underset{K}{\arg\min} \, (J(K) \; + \; \gamma \, g(K))$$



ALGORITHM: **alternating direction method of multipliers**

Performance index

- **Energy of power network without inter-area modes**
  - ⋆ inspired by slow coherency theory

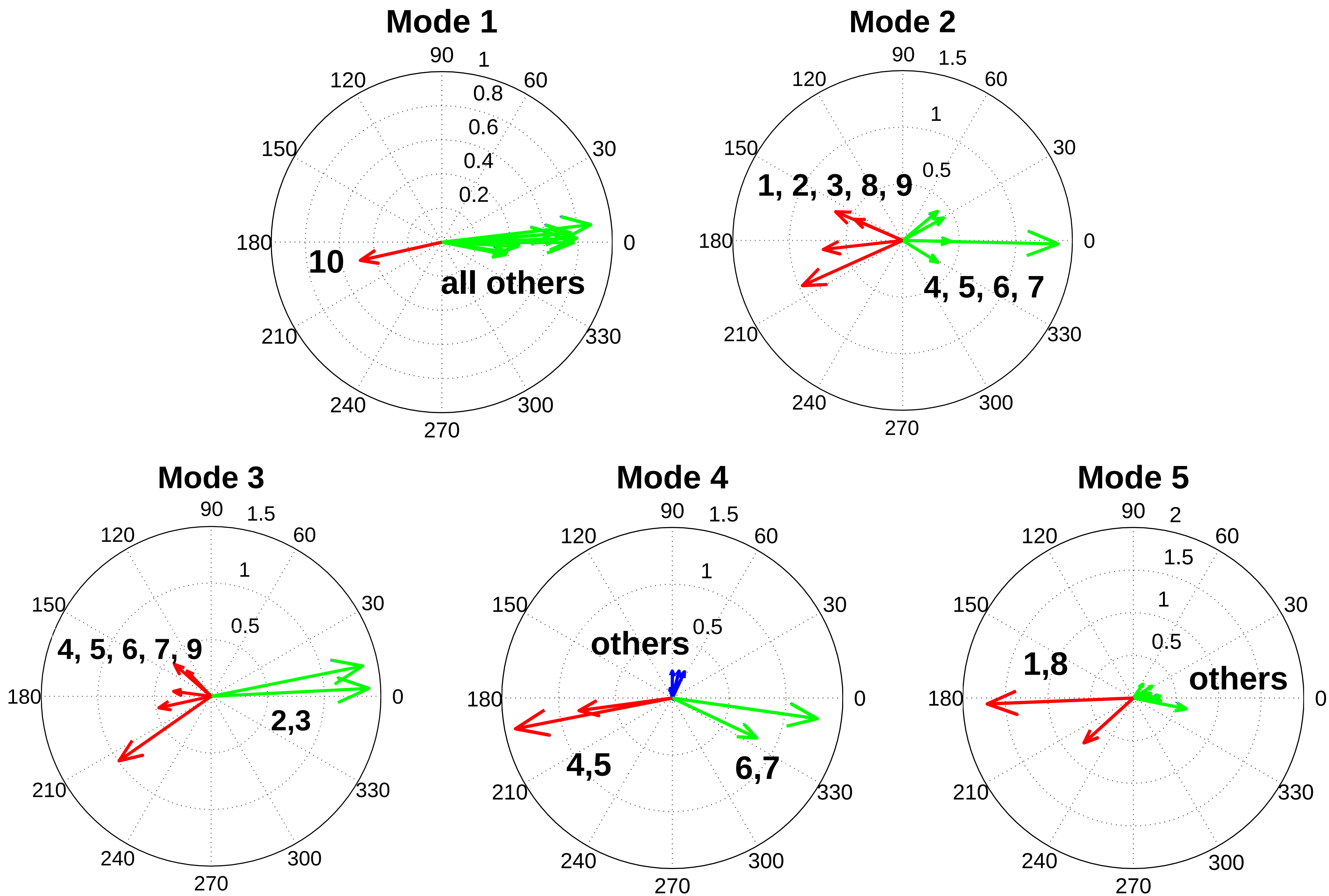
$$J \;:=\; \lim_{t \,\to\, \infty} \mathcal{E}\left(\theta^T(t)\, Q_\theta\, \theta(t) \;+\; \dot{\theta}^T(t)\, \dot{\theta}(t) \;+\; u^T(t)\, u(t)\right)$$

$$Q_\theta \;:=\; \epsilon\, I \;+\; \left(I \;-\; \frac{1}{N}\, \mathbb{1}\mathbb{1}^T\right)$$

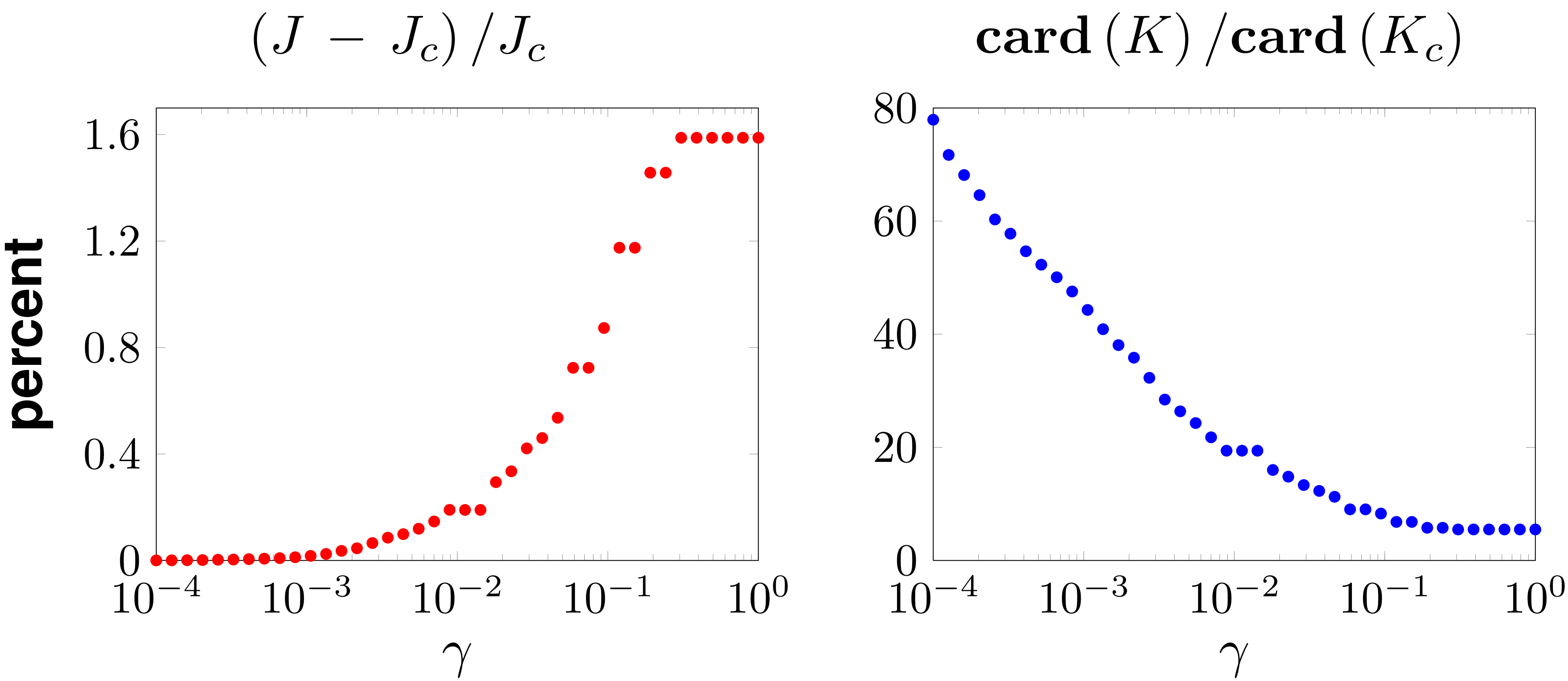
  - ⋆ other choices possible

Open-loop dynamics

- **Dominant inter-area modes with local PSSs**



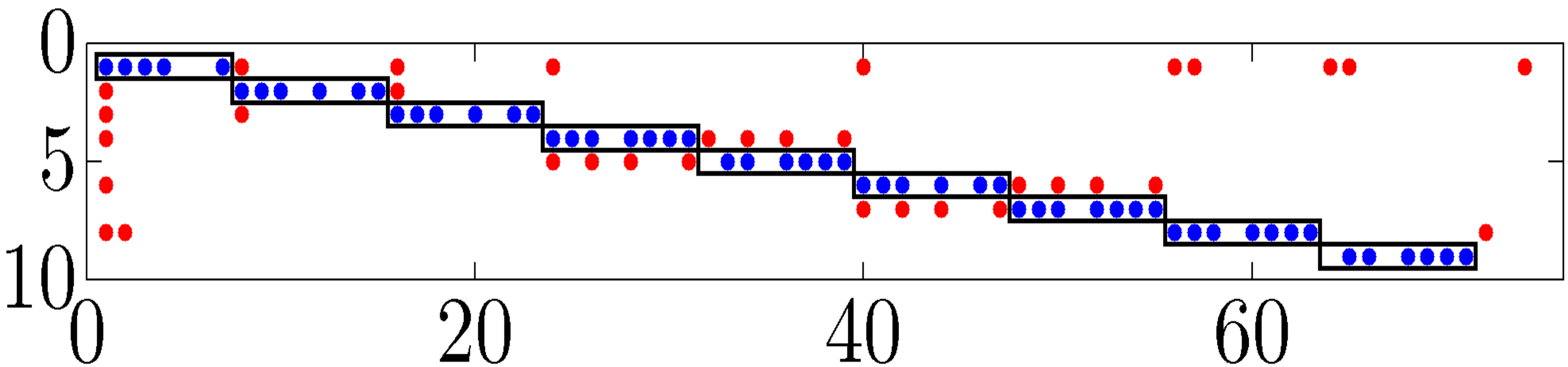
Performance vs sparsity



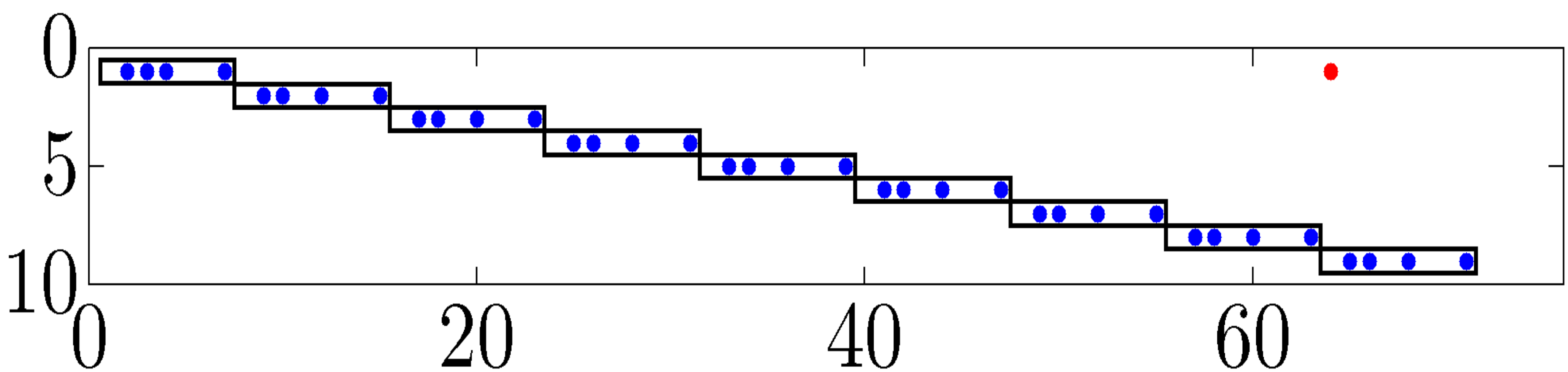
$$\gamma = 1 \xrightarrow{\text{relative to } K_c} \begin{cases} 1.6\,\% & \text{performance loss} \\ 5.5\,\% & \text{non-zero elements in } K \end{cases}$$

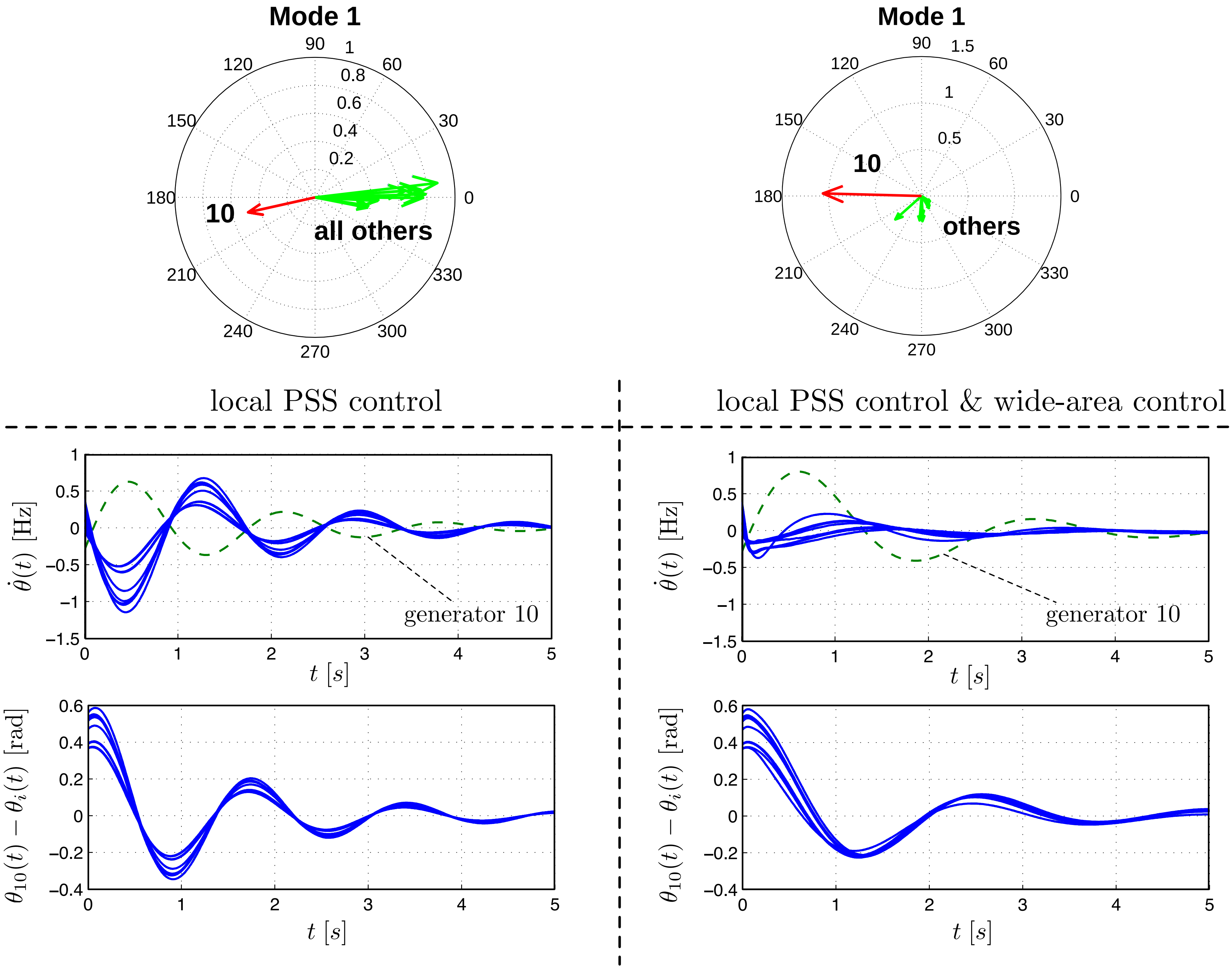
Signal exchange network

$$\gamma = 0.0289, \ \mathbf{card}\,(K) = 90$$

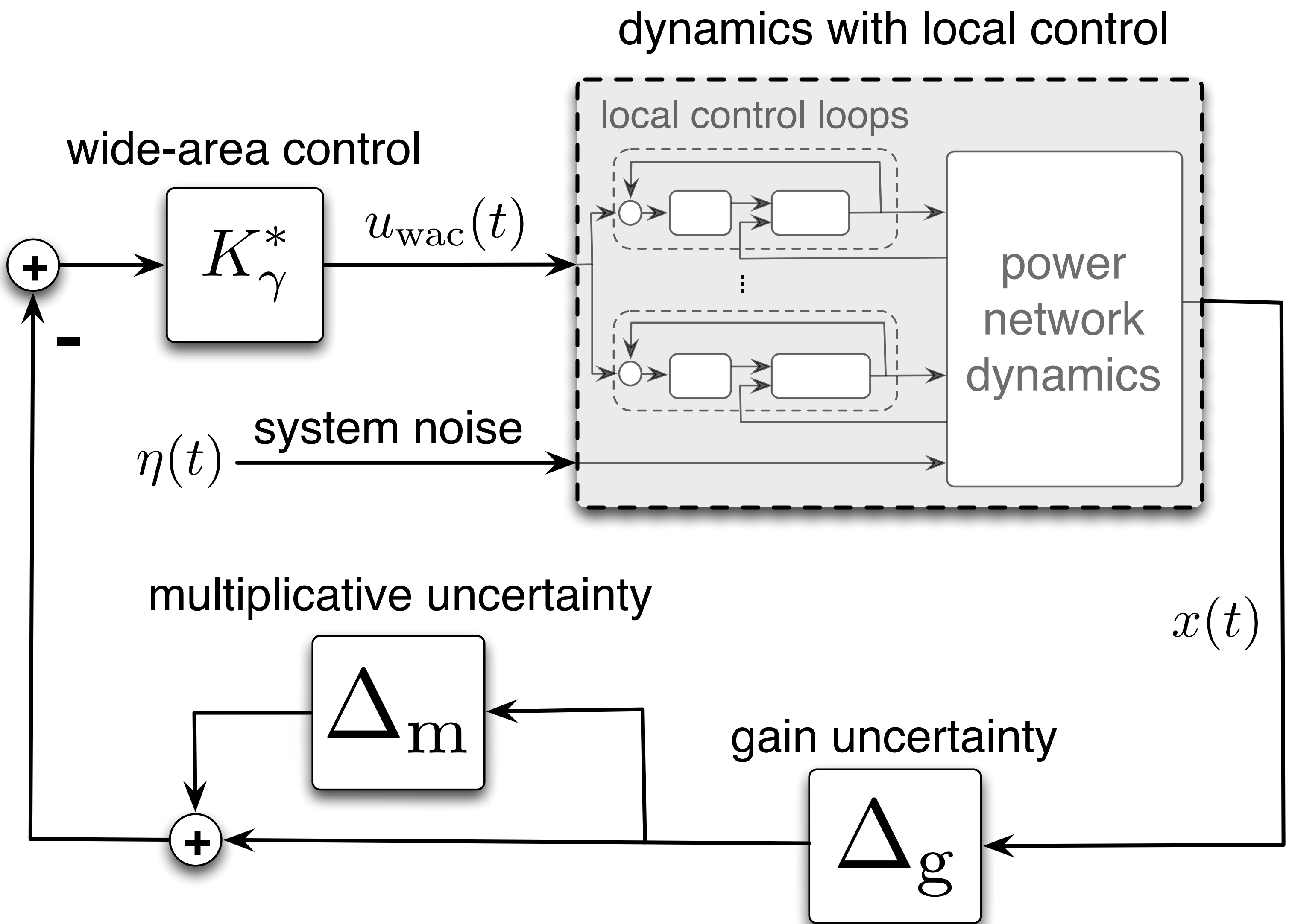


$$\gamma = 1, \ \mathbf{card}\,(K) = 37$$



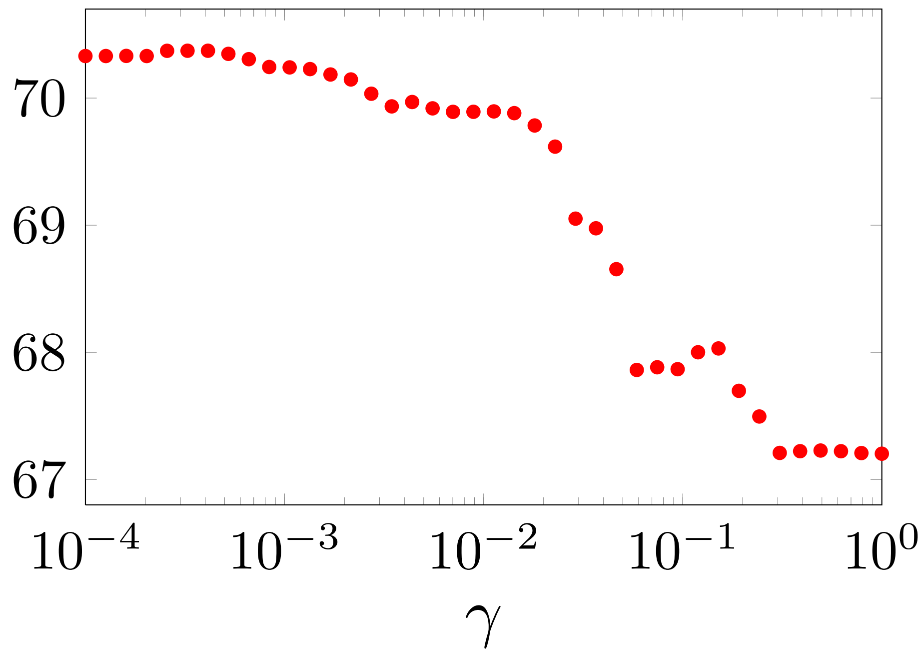

Mode 1
10
all others
Mode 1
10
others
local PSS control
local PSS control & wide-area control
$\dot{\theta}(t)$ [Hz]
generator 10
t [s]
$\theta_{10}(t) - \theta_i(t)$ [rad]
t [s]
$\dot{\theta}(t)$ [Hz]
generator 10
t [s]
$\theta_{10}(t) - \theta_i(t)$ [rad]
t [s]

- **Robustness?**

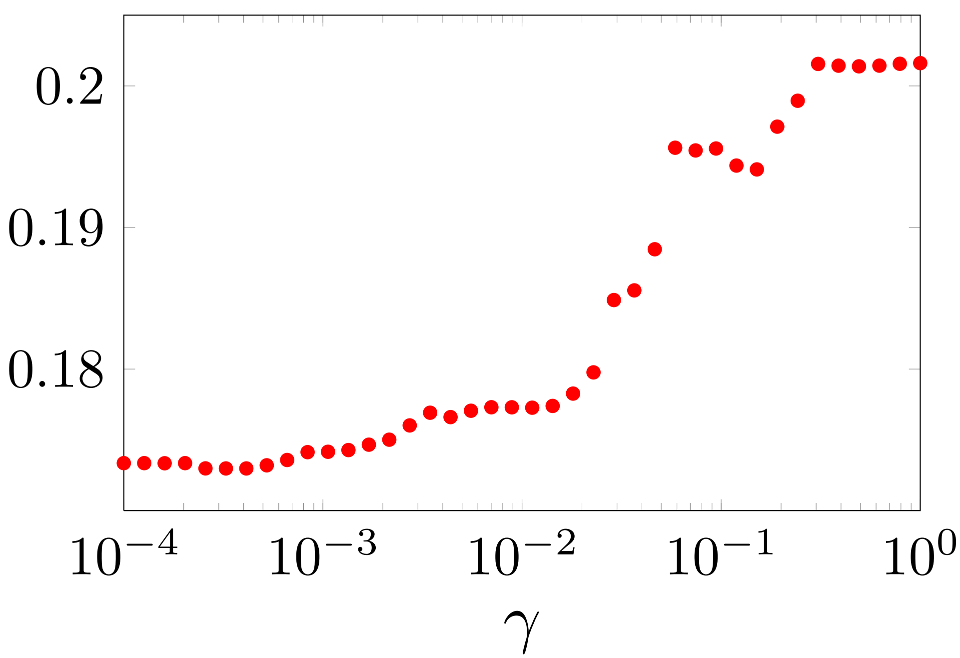


dynamics with local control
local control loops
wide-area control
K_γ^*
$u_{\mathrm{wac}}(t)$
power network dynamics
+
-
system noise
$\eta(t)$
multiplicative uncertainty
$x(t)$
Δ_{m}
gain uncertainty
Δ_{g}
+

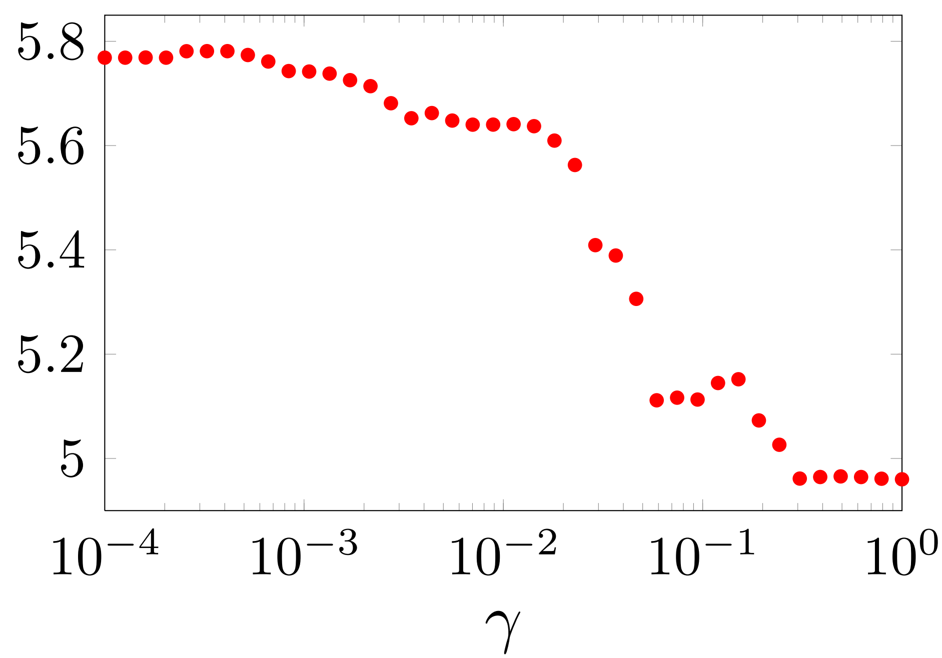
multivariable phase margin



multivariable gain reduction margin



multivariable gain amplification margin



Summary and outlook

- SPARSITY-PROMOTING OPTIMAL CONTROL
  - ⋆ Performance vs sparsity tradeoff

    Lin, Fardad, Jovanović, IEEE TAC '13 (in press; arXiv:1111.6188)
  - ⋆ Software

    www.umn.edu/∼mihailo/software/lqrsp/

- WIDE-AREA CONTROL OF POWER NETWORKS
  - ⋆ Remedy against inter-area oscillations
  - ⋆ IEEE New England power grid model

- OPEN QUESTIONS
  - ⋆ Extension to structure-preserving descriptor models
  - ⋆ Theoretic analysis of robustness degradation
  - ⋆ Exploit the rotational symmetry of the models