JST-NSF-RCN WS on Distributed EMS

Fundamental Theory for Scalable Power Systems Control

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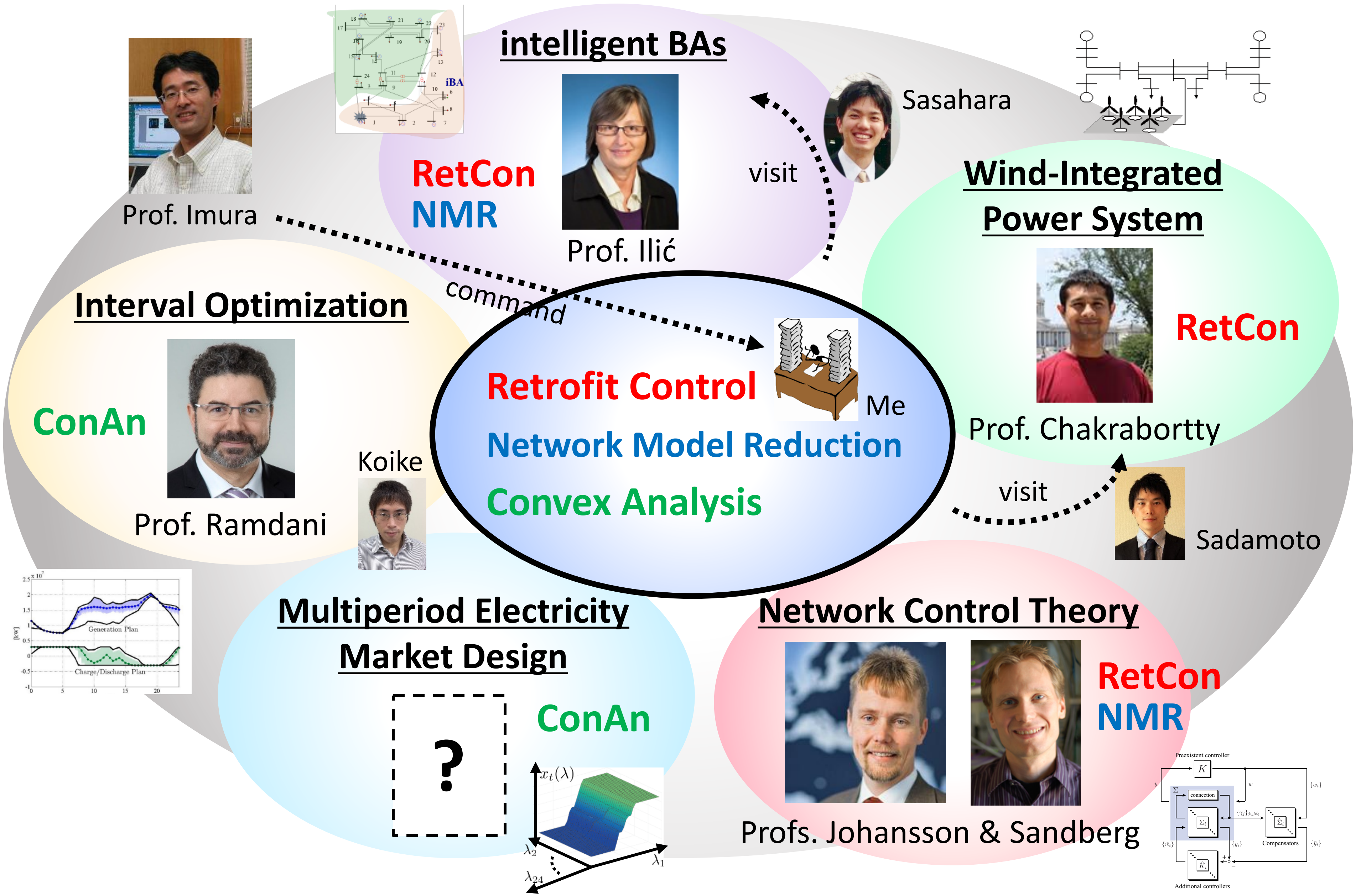
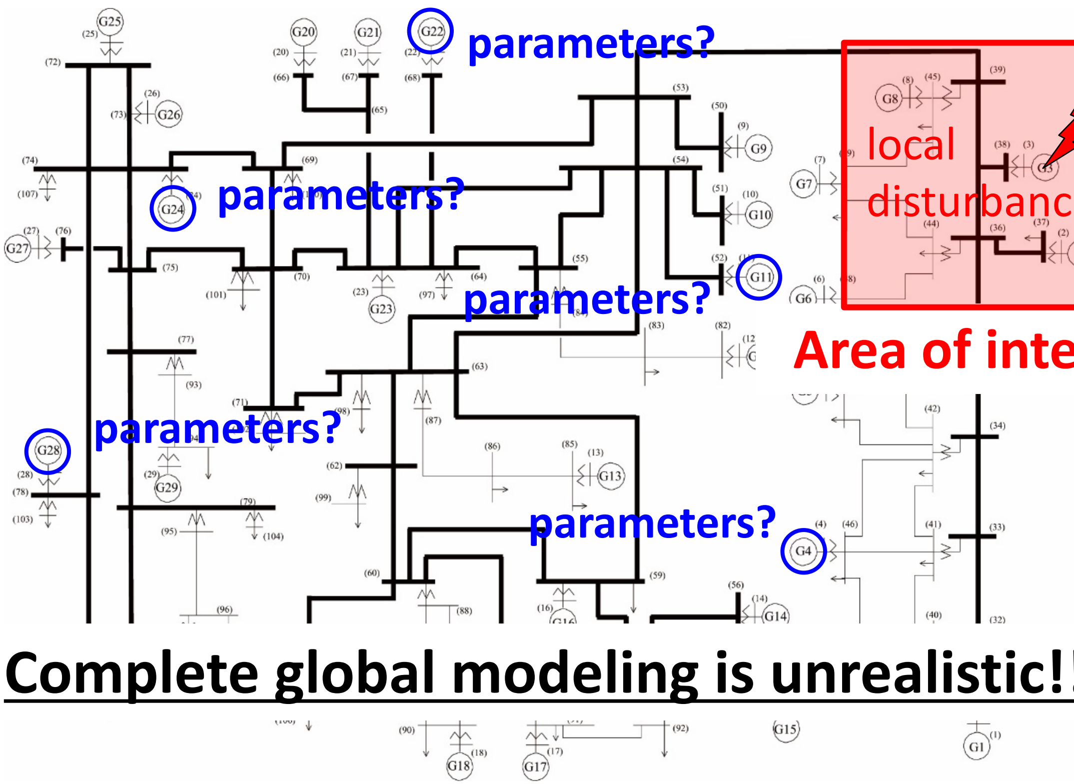
Collaborative Works Overview

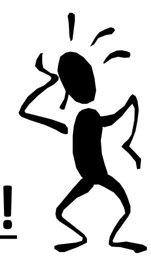


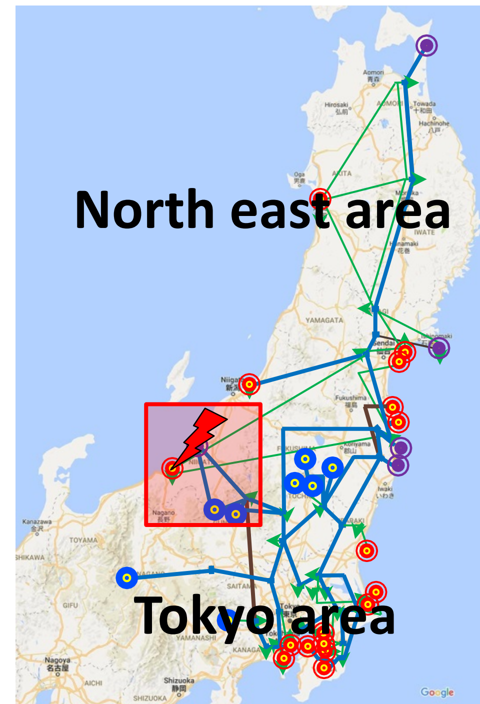
Large-Scale Power Systems Control

IEEJ EAST30 Model (stable system composed of 30 generators)



Complete global modeling is unrealistic!!

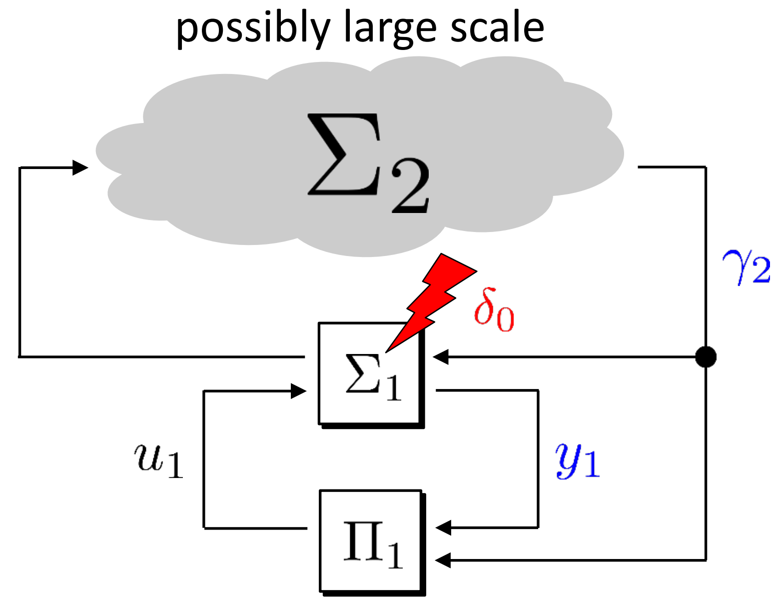




Controller design by local model?

Stability? Better performance?

Problem Formulation: Retrofit Control



Subsystem of interest (model available)

$$\Sigma_1 : \begin{cases} \dot{x}_1 = \boldsymbol{A}_1 x_1 + \boldsymbol{L}_1 \gamma_2 + \boldsymbol{B}_1 u_1 \\ y_1 = \boldsymbol{C}_1 x_1 \end{cases}$$

Other subsystem(s) (model unavailable)

$$\Sigma_2 : \begin{cases} \dot{x}_2 = A_2 x_2 + L_2 \Gamma_1 x_1 \\ \gamma_2 = \Gamma_2 x_2 \end{cases}$$

✓ $x_1(0) = \delta_0, \; x_2(0) = 0, \; \|\delta_0\| \leq 1$

Assumption: (i) y_1, γ_2 are measurable
(ii) the preexisting system without Π_1 is stable

【Problem】 Find a **retrofit controller** $\Pi_1 : u_1 = \mathcal{K}_1(y_1, \gamma_2)$ such that
(a) the whole system is **kept stable** and (b) $\|x_1\|_{\mathcal{L}_2}$ **is made small** for any δ_0.

Hierarchical State-Space Expansion

Coupled state equation of Σ_1 and Σ_2

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} = \begin{bmatrix} \boldsymbol{A}_1 & \boldsymbol{L}_1\mathit{\Gamma}_2 \\ L_2\mathit{\Gamma}_1 & A_2\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix} + \begin{bmatrix}\boldsymbol{B}_1\\ 0\end{bmatrix}u_1$$

stable (assumption)

state-space expansion
to **cascade realization**

Hierarchical realization $(2n_1 + n_2)$-dim

$$\begin{bmatrix}\dot{\xi}_1\\ \dot{\xi}_2\end{bmatrix} = \begin{bmatrix} \boldsymbol{A}_1 & \boldsymbol{L}_1\mathit{\Gamma}_2 \\ L_2\mathit{\Gamma}_1 & A_2\end{bmatrix}\begin{bmatrix}\xi_1\\ \xi_2\end{bmatrix} + \begin{bmatrix}0\\ L_2\mathit{\Gamma}_1\end{bmatrix}\hat{\xi}_1$$

stable

decoupled!

$$\dot{\hat{\xi}}_1 = \boldsymbol{A}_1\hat{\xi}_1 + \boldsymbol{B}_1 u_1$$

stabilized by u_1

【Lemma】 If $\xi_1(0) = 0,\ \xi_2(0) = 0$ and $\hat{\xi}_1(0) = \delta_0$

then $x_1(t) \equiv \xi_1(t) + \hat{\xi}_1(t)$ and $x_2(t) \equiv \xi_2(t)$ for any $u_1(t)$.

Localized Controller Design

Hierarchical realization

$$\begin{bmatrix} \dot{\xi}_1 \\ \dot{\xi}_2 \end{bmatrix} = \underbrace{\begin{bmatrix} \boldsymbol{A}_1 & \boldsymbol{L}_1 \Gamma_2 \\ L_2 \Gamma_1 & A_2 \end{bmatrix}}_{\text{stable}} \begin{bmatrix} \xi_1 \\ \xi_2 \end{bmatrix} + \begin{bmatrix} 0 \\ L_2 \Gamma_1 \end{bmatrix} \hat{\xi}_1$$

model available!

$$\dot{\hat{\xi}}_1 = \boldsymbol{A}_1 \hat{\xi}_1 + \boldsymbol{B}_1 u_1$$

【Lemma】 Design a controller $u_1 = \boldsymbol{K}_1 \boldsymbol{C}_1 \hat{\xi}_1$ such that

$\dot{\hat{\xi}}_1 = (\boldsymbol{A}_1 + \boldsymbol{B}_1 \boldsymbol{K}_1 \boldsymbol{C}_1)\hat{\xi}_1$ is stable and $\|\hat{\xi}_1\|_{\mathcal{L}_2} \leq \mu_1.$

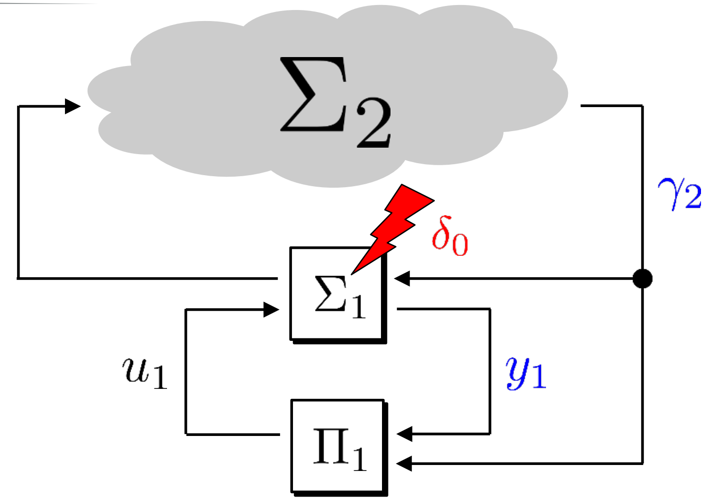
Then the closed-loop system is stable and $\|\xi_1 + \hat{\xi}_1\|_{\mathcal{L}_2} \leq \alpha_1 \mu_1, \ \forall \delta_0.$ (constant)

✓ Generalization to dynamical controller design is straightforward

How to implement $u_1 = \boldsymbol{K}_1 \boldsymbol{C}_1 \hat{\xi}_1$ **??** ($\neq y_1$)

Controller Implementation

How to implement $u_1 = \boldsymbol{K}_1 \boldsymbol{C}_1 \hat{\xi}_1$ **??**



$$\boldsymbol{C}_1 \hat{\xi}_1(t) \equiv \boldsymbol{C}_1 x_1(t) - \boldsymbol{C}_1 \xi_1(t)$$

$$\Gamma_2 \xi_2(t) \equiv \Gamma_2 x_2(t) \equiv \gamma_2(t)$$

$$\dot{\xi}_1 = \boldsymbol{A}_1 \xi_1 + \boldsymbol{L}_1 \Gamma_2 \xi_2 \quad \text{with} \quad \xi_1(0) = 0$$

$\hat{x}_1(t) \equiv \xi_1(t)$

$$\Longleftrightarrow \quad \dot{\hat{x}}_1 = \boldsymbol{A}_1 \hat{x}_1 + \boldsymbol{L}_1 \gamma_2 \quad \text{with} \quad \hat{x}_1(0) = 0$$

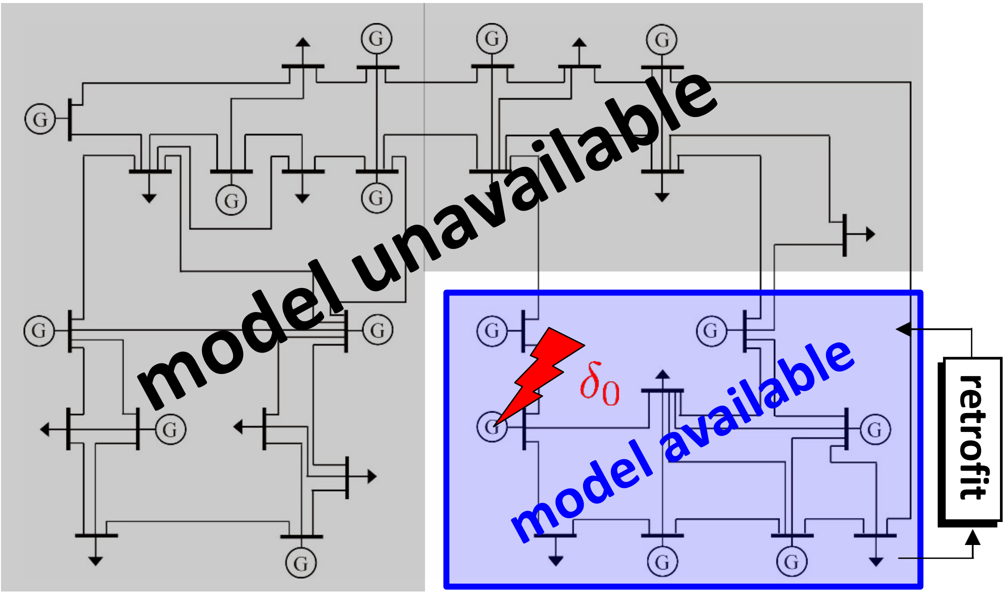
【Theorem】 The closed-loop system with the retrofit controller

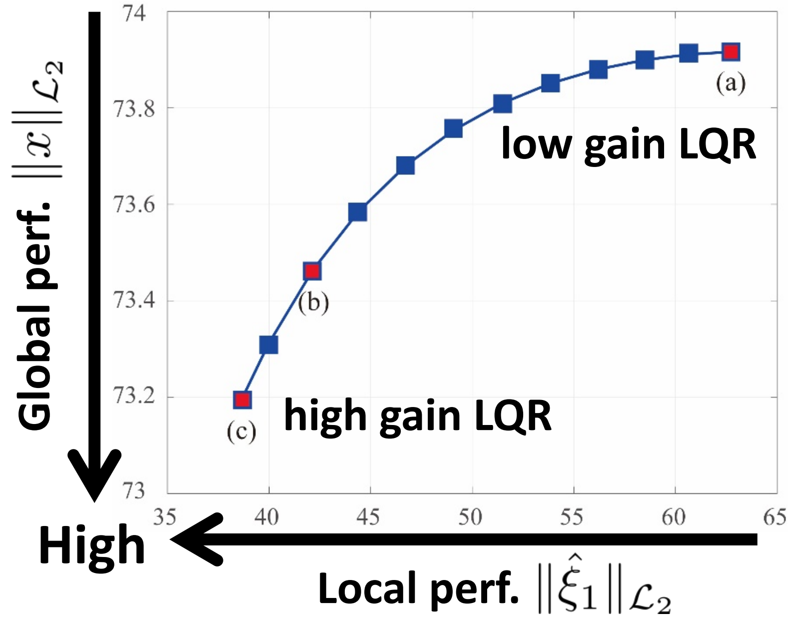
$$\Pi_1 : \begin{cases} \dot{\hat{x}}_1 = \boldsymbol{A}_1 \hat{x}_1 + \boldsymbol{L}_1 \gamma_2 \\ u_1 = \boldsymbol{K}_1 (y_1 - \boldsymbol{C}_1 \hat{x}_1) \end{cases}$$

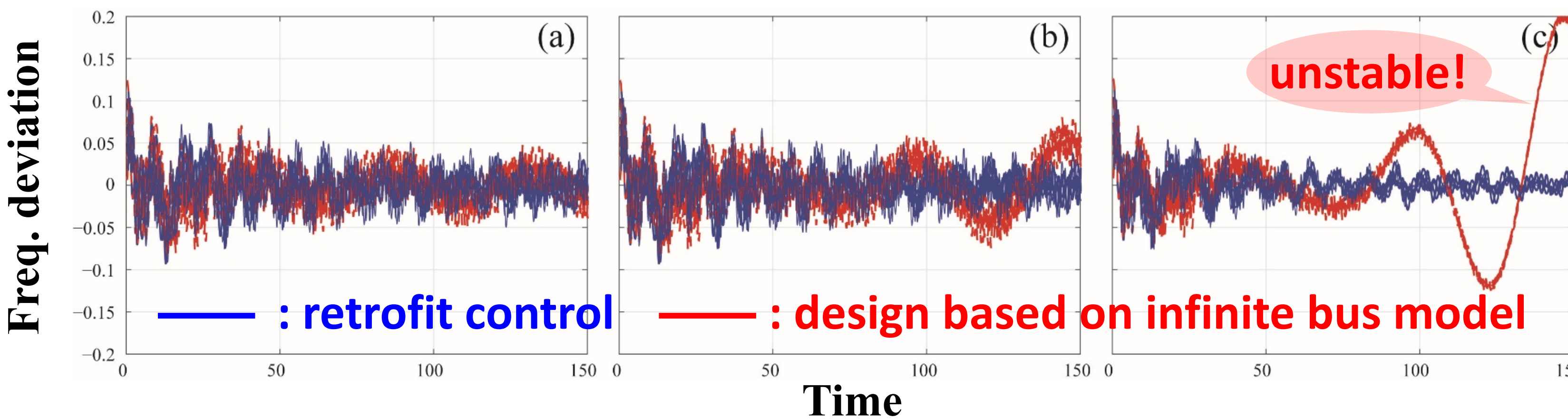
Localizing compensator

is internally stable and it satisfies $\|x_1\|_{\mathcal{L}_2} \le \alpha_1 \mu_1, \ \forall \delta_0.$

Demonstration by Swing Equation Model



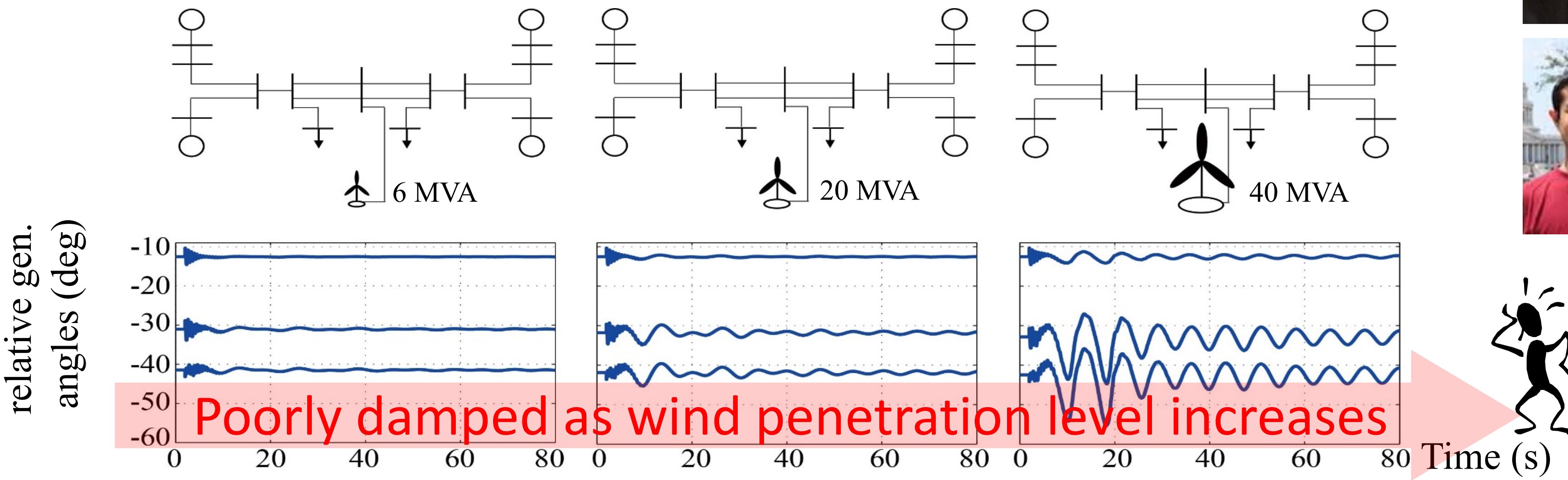


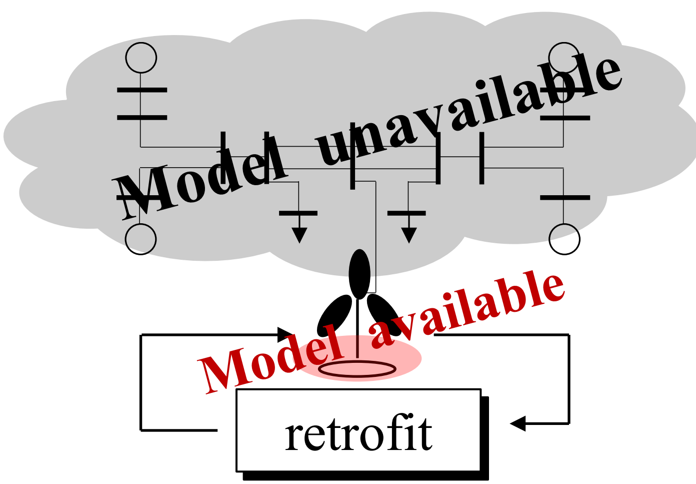


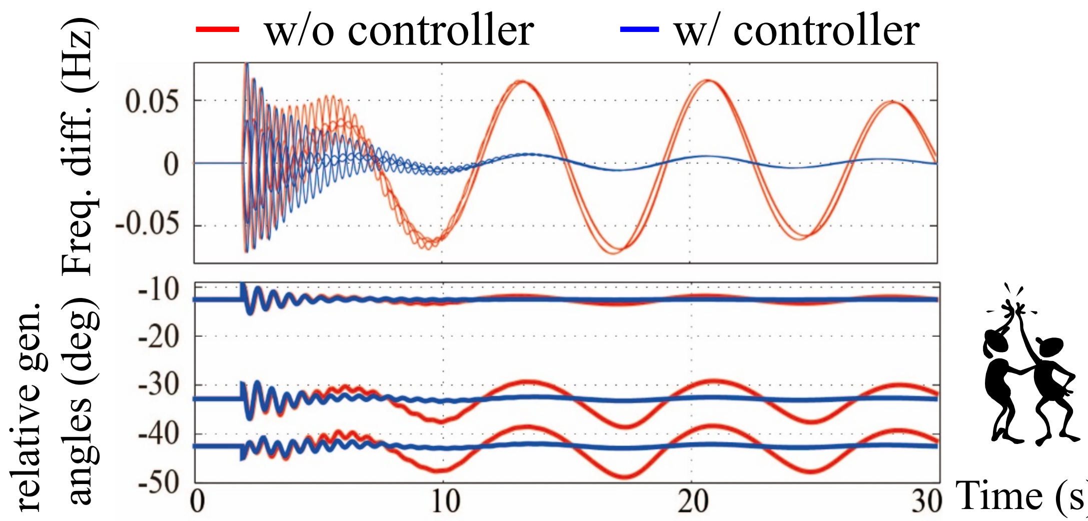
Scalable development of large-scale stable network systems based on distributed design and implementation of multiple retrofit controllers

Enhanced Damping of Wind Power Systems

by T. Sadamoto, A. Chakrabortty







Retrofit control of wind power plant can enhance damping performance

Concluding Remarks

- **Retrofit control**
  - Localization of controller design and implementation
  - Stability guarantee and control performance improvement
- **Hierarchical state-space expansion**
  - Redundant realization with cascade structure
  - Systematic analysis for stability and control performance

General Theory: T. Ishizaki, T. Sadamoto, J. Imura, H. Sandberg, K. H. Johansson: Retrofit Control: Localization of Controller Design and Implementation. *arXiv*

Power Systems Application: T. Sadamoto, A. Chakrabortty, T. Ishizaki, J. Imura: A Retrofitting-Based Supplementary Controller Design for Enhancing Damping Performance of Wind Power Systems. *ACC2017*

Thank you for your attention!