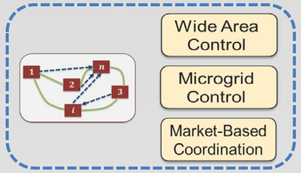
Project 1.5

Resilience of Large-Scale Distributed Control Systems

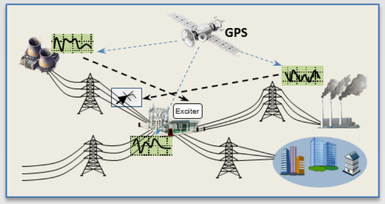
Wei Zhang, Laurentiu Marinovici, Jianming Lian, and Antonio Conejo (OSU)

Background and Objectives

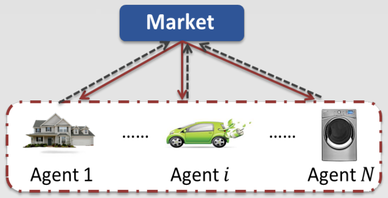
- Communications among subsystems improve performance, but also increase vulnerability
- **Objectives**: Establish framework to analyze and quantify resilience for distributed control systems
- Focus on two different distributed control paradigms in power systems



Wide Area Control (Distributed)



Transactive (Hierarchically Distributed)



Methodology

- **Resilience metric**: relative degradation of performance under attacks

Resilience quantification for WAC

- **Model**: N bus network-reduced model under WAC

$$\dot{x}_i = A_{ii}x_i + \sum_{j\in N_i} A_{ij}x_j + B_i u_i$$
$$u_i = \underbrace{K_{ii}x_i}_{\text{Local control modification}} + \underbrace{\sum_{j\in N_i} K_{ij}x_j}_{\text{Wide area control}}$$

- **Attack**: Loss of communication attack represented by binary matrix α

cl-sys: $\dot{x} = (A + BK \circ \alpha)x \triangleq A(\alpha)x$

- **Direct formulation**: Based on eigenvalue or H_2 norm:

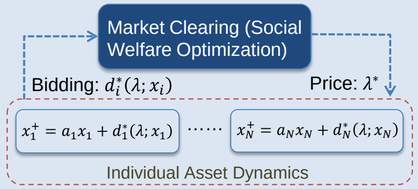
$$\gamma_0^* \triangleq \max_{\alpha\in\mathcal{A}_0} \textbf{Performance}\ (\alpha)$$

Challenges:

- Nonconvex problem;
- Combinatorial attack space

Initial Study of Market Stability

- **Reverse engineering:**
  - Bidding → utility optimizer
  - Market Clearing → social welfare optimization
  - Market Stability → dynamical systems coupled through centralized optimization



Challenges:

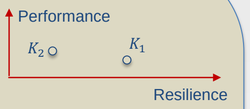
- Constraints on both control and state
- LMI-based condition not numerically tractable

Results

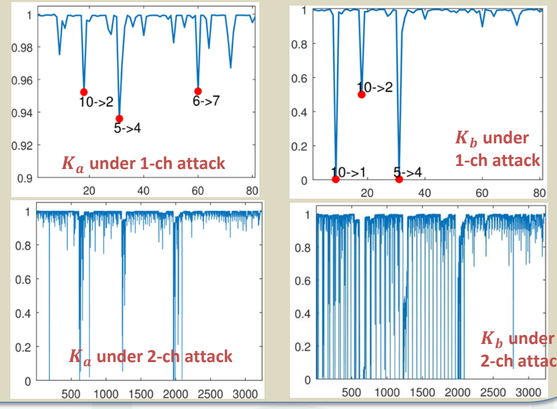
- **Relaxation**: $\mathcal{A} = \mathrm{conv}(\mathcal{A}_0)$ relaxed attack space

$$\gamma_{LP}^* \triangleq \max_{\alpha\in\mathcal{A}} \min_{P\in\mathcal{P}} \lambda_{\max}(A(\alpha)^T P + PA(\alpha))$$

- **Theorem:** Resilient ***if*** $\gamma_{LP}^* < 0$; not resilient ***only if*** $\gamma_{LP}^* \geq 0$
- **Developed** efficient algorithm to compute resilience index

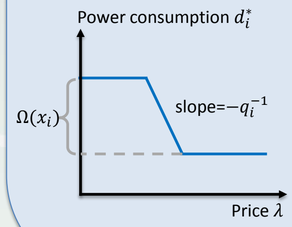


Validation using the IEEE 39 Bus System

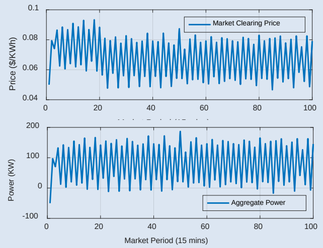


Multi-Period Market Stability

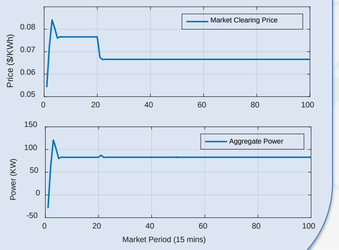
- **Stability criterion:** $|a_i + \phi_i r_i| < 1$ for each agent, where ϕ_i depends on q_i^{-1} and aggregate parameters
- **Implication & Significance**
  - Bidding functions with shallower slopes improve the stability
  - Market stability criterion can be easily checked in a decentralized way
- **Simulation setup:**
  - 100 residential energy storages with option to sell energy back to the grid
  - Energy capacity: 12~15 KWh
  - Charging/discharging rate: 6~8 KW
  - Market period: 15 mins
  - Base price change from 0.06 \$/KWh to 0.05 \$/KWh at the 5th hour



Bidding function



Unstable Market $q_i = 0.3$



Stable Market $q_i = 0.8$

CCSI Control of Complex Systems Initiative

Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

U.S. DEPARTMENT OF ENERGY

PNNL-SA-XXXXX