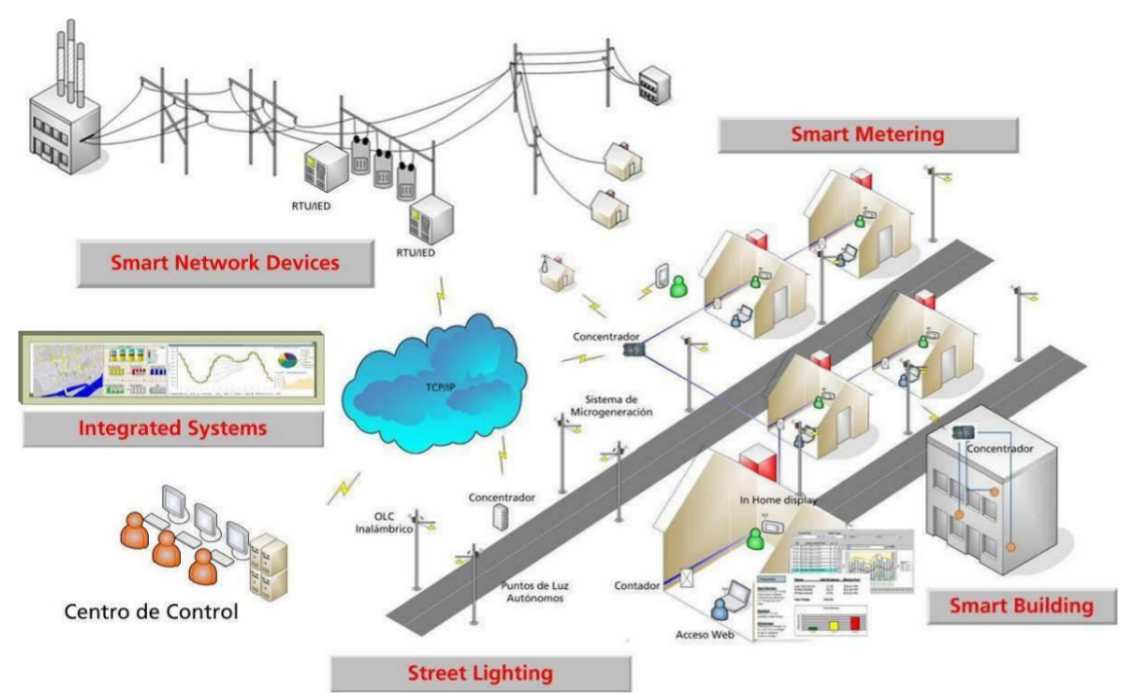
CPS: Synergy: Certifiable, Attack-resilient Submodular Control Framework for Smart Grid Stability (CNS-1544173)

Principal Investigators: Linda Bushnell*, Daniel Kirschen*, Radha Poovendran*, and Andrew Clark⁺
*Department of Electrical Engineering, University of Washington, Seattle {lb2, kirschen, rp3}@uw.edu
⁺Department of Electrical and Computer Engineering, Worcester Polytechnic Institute, aclark@wpi.edu

Control and Stability of the Smart Grid

- Power system is a societal-level cyber-physical system
- Increasing demand and uncertain renewable power sources are pushing the power system close to its operation limits
- Cyber-enabled grid has multiple entry points for malicious cyber adversaries



Scientific Questions Addressed

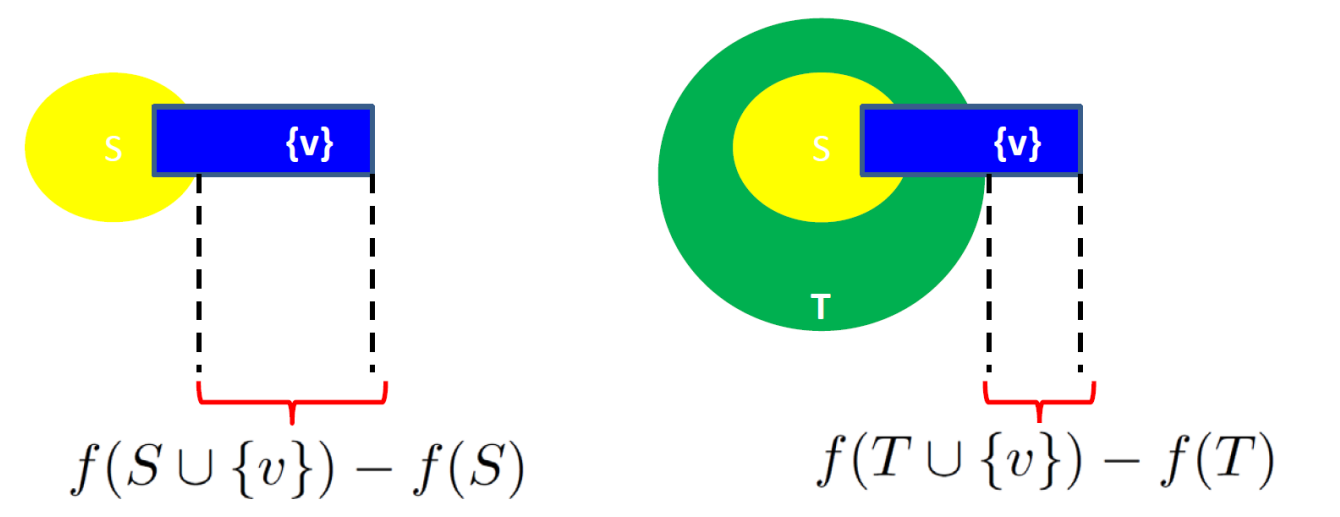
- How to develop smart grid control algorithms with provable stability guarantees?
- How to ensure scalability to large power systems?
- How to provide stability guarantees in the presence of cyber attacks by malicious adversaries?

Submodularity and Bounded Curvature

- "Diminishing returns" property of set functions
- For any sets $S \subseteq T \subseteq V$ and $v \in V \setminus T$,

$$f(S \cup \{v\}) - f(S) \geq f(T \cup \{v\}) - f(T)$$

- Example: Set cover, f(S) = number of elements in S



- Curvature: Bound on marginal benefit from adding any single element to set S
- Leads to efficient, provably optimal algorithms for solving otherwise-intractable discrete optimization problems

Our Proposed Submodular Control Framework

- Formulate combinatorial power system control problems (e.g., selecting devices to inject reactive power) in optimization framework
- Optimality guarantees arise from submodularity (voltage stability) and bounded curvature (small-signal and transient stability).
- Provide verifiable power system stability
- Reduce the need for exhaustive search algorithms, enable real-time control

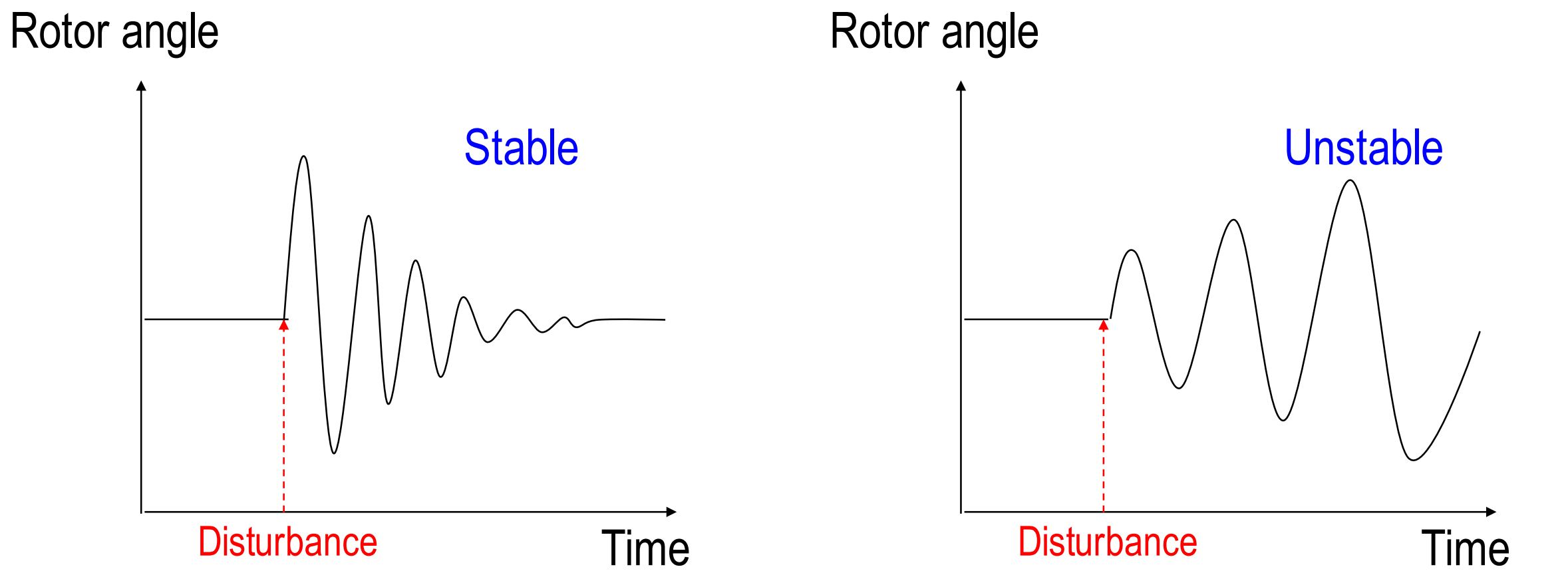
Intellectual Merit

- Identify and exploit inherent computational structures of physical dynamics of power systems
- Criteria include voltage, small-signal, and transient stability
- Develop efficient distributed algorithms to ensure scalability
- Resilience to false data, spoofing, and denial-of-service attacks

Broader Impact

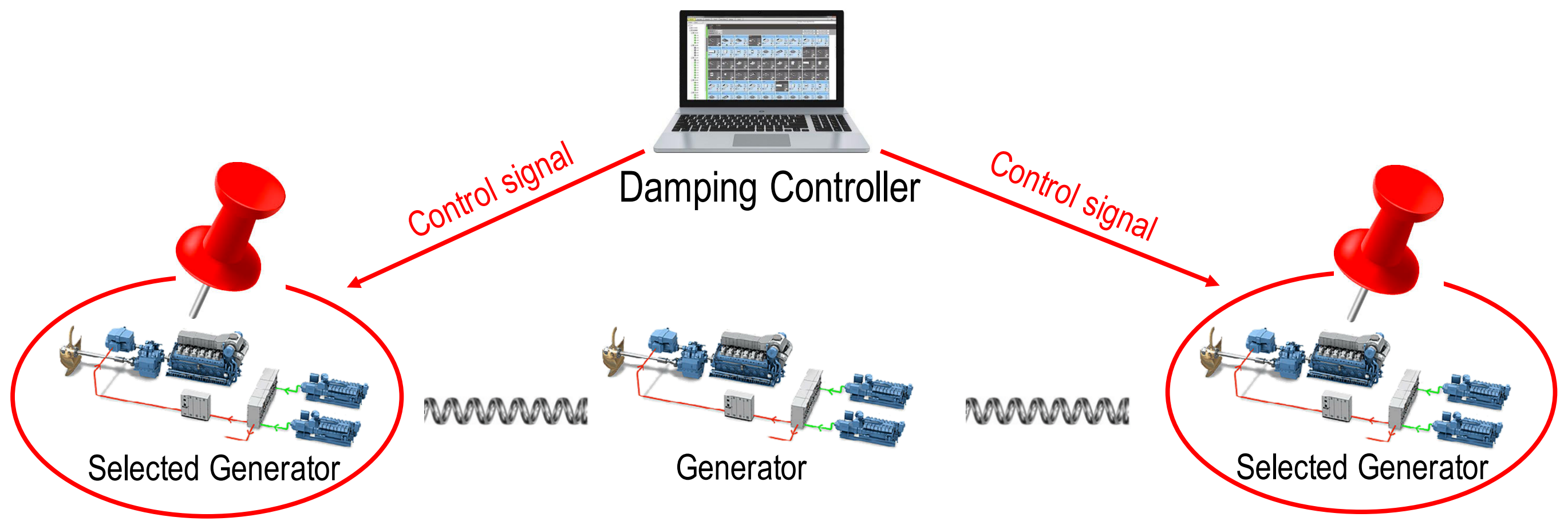
- Improving the stability and reliability of the smart grid and facilitate integration of distributed, renewable energy sources
- Scalable and certifiable control algorithms will have applications to transportation, robotics, and health.
- Graduate-level courses on smart grid security

Small Signal Stability

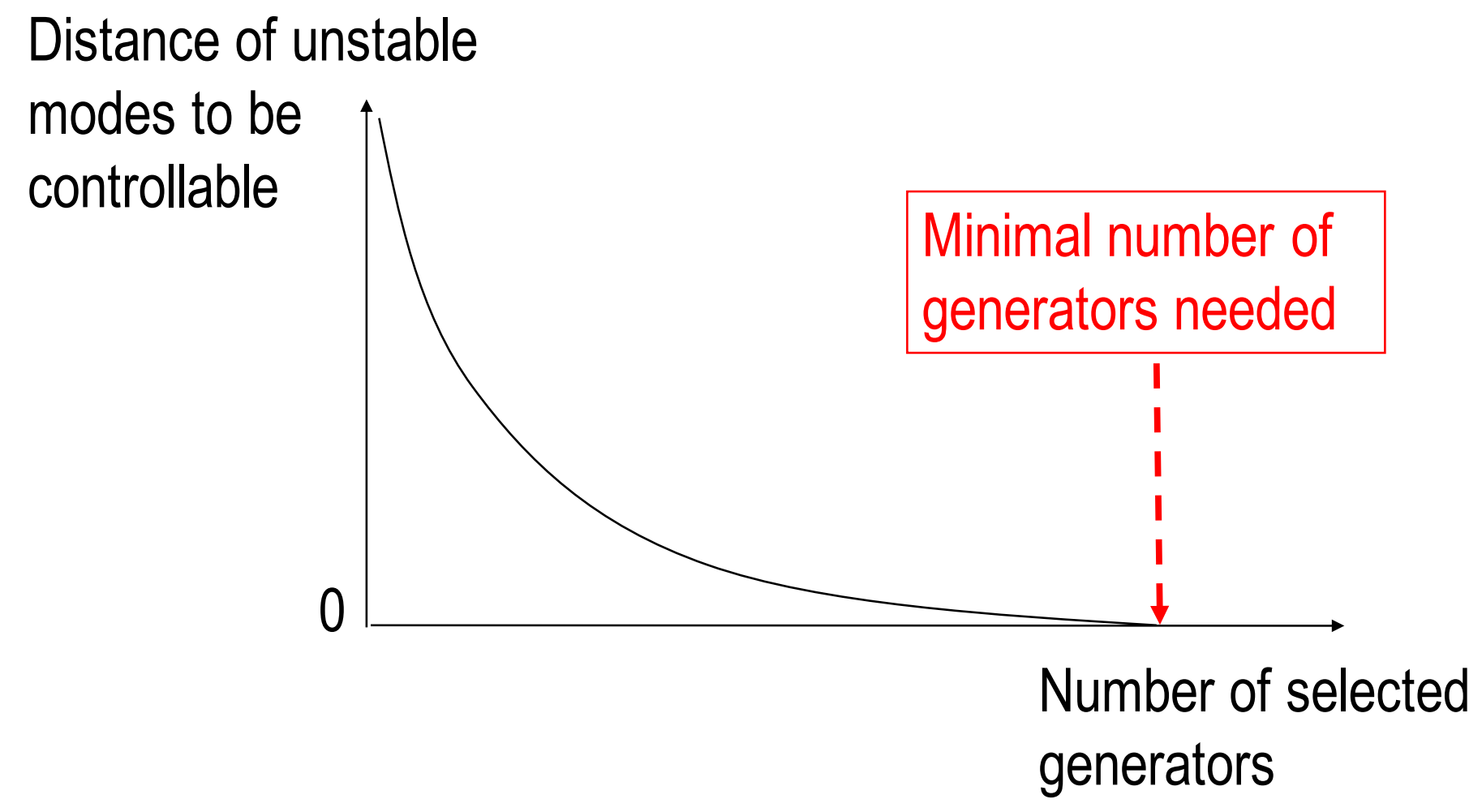


- **Small-signal stability**: Stability of rotor angles following minor disturbances
- Set of generators must exert additional control in order to damp unstable oscillating modes of the system

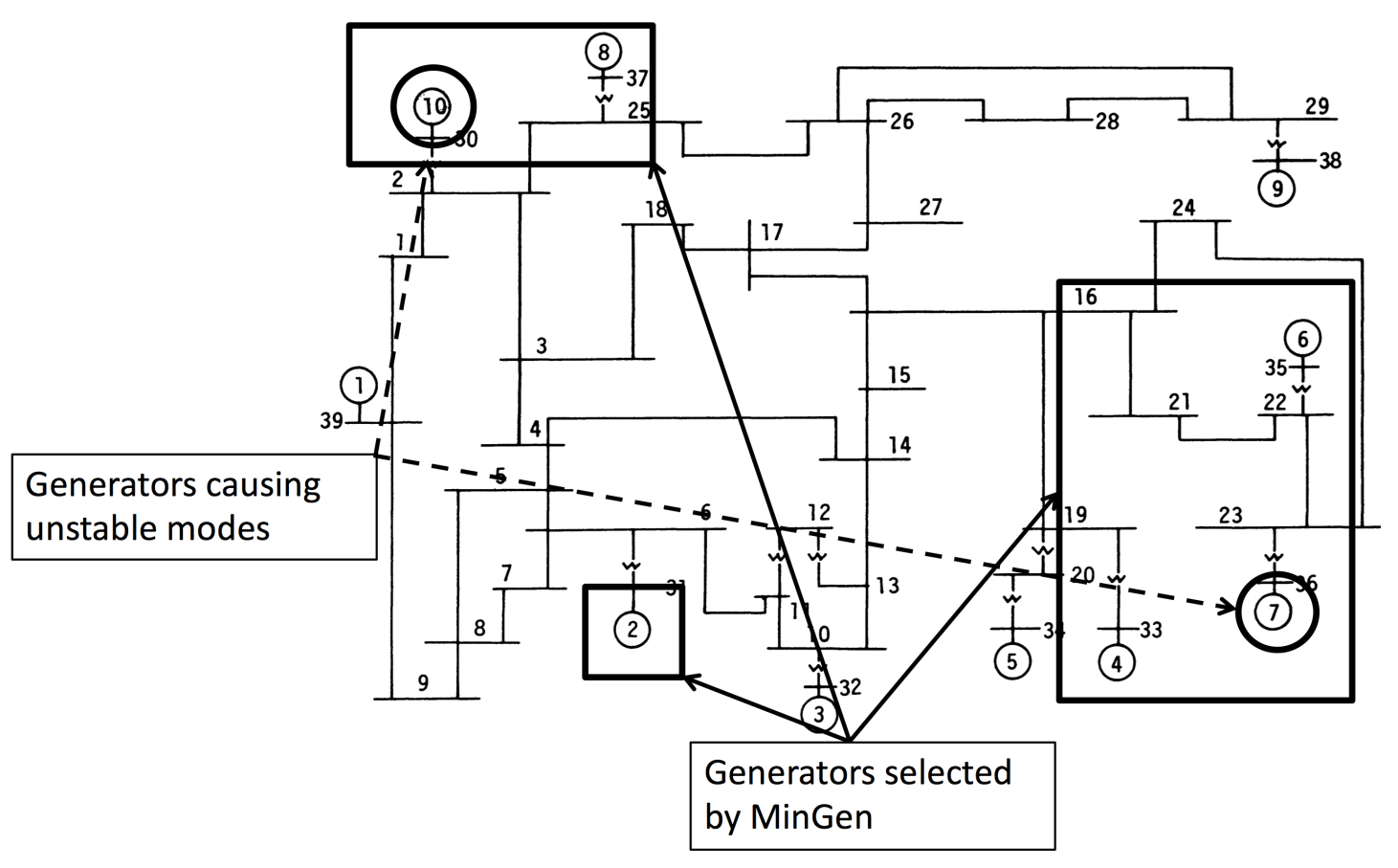
Generator Selection for Small Signal Stability

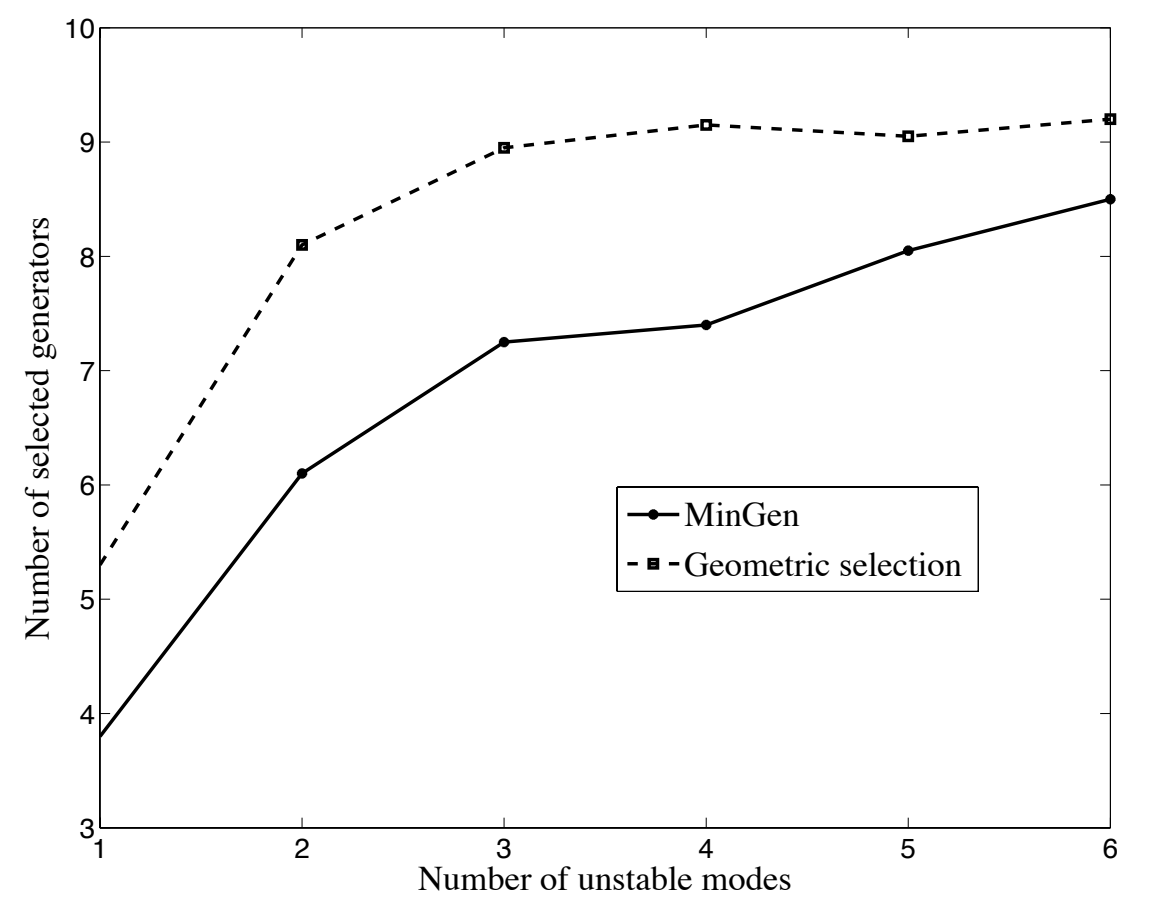


- Involving a new generator in the centralized control to maintain small signal stability is costly (changing generator configuration, more computational overhead, etc)
- Selecting the **minimal number of generator** to exert control is inherently a combinatorial optimization problem
- Problem formulation: Select a minimal set of generators that satisfy **controllability** and **observability** of unstable modes
- Distance of unstable modes from controllable/observable subspace: **Monotone decreasing** function of set of generators with **bounded curvature**



- **MinGen:** Greedy algorithm for minimal generator set selection
- Polynomial-time complexity
- Optimality bound characterized using condition number of system matrix

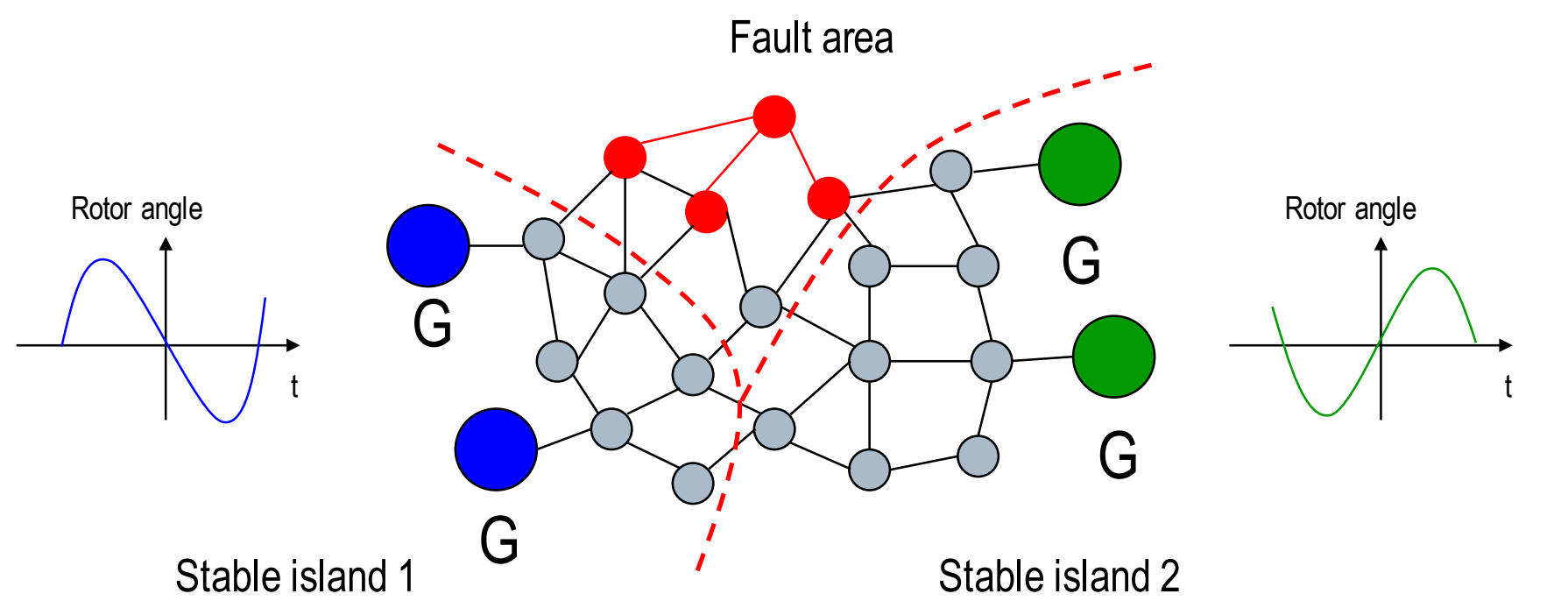




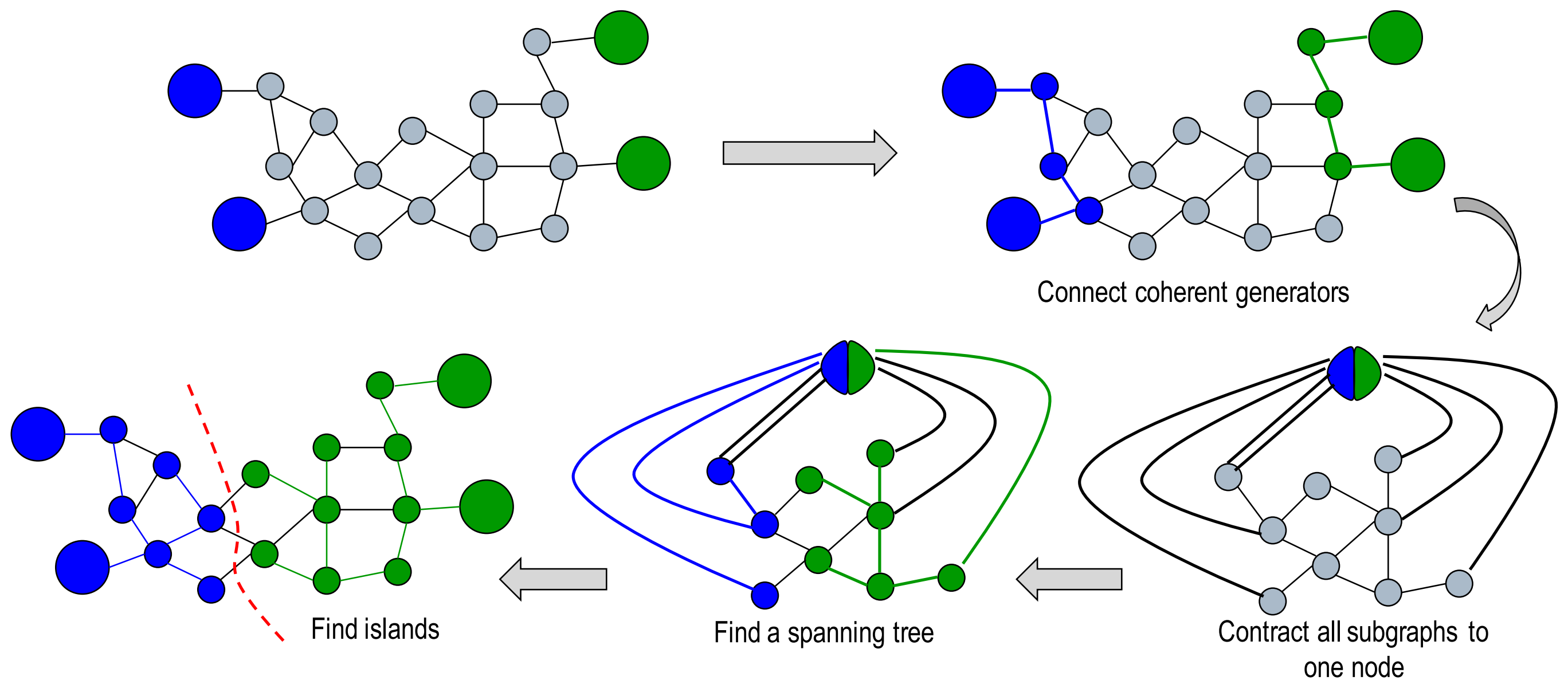
- Simulation study on IEEE 39-bus test case: Proposed approach identifies the set of generators to resolve small signal instability
- The number of generators required is significantly reduced compared to state of art approach

Controlled Islanding for Cascading Failure

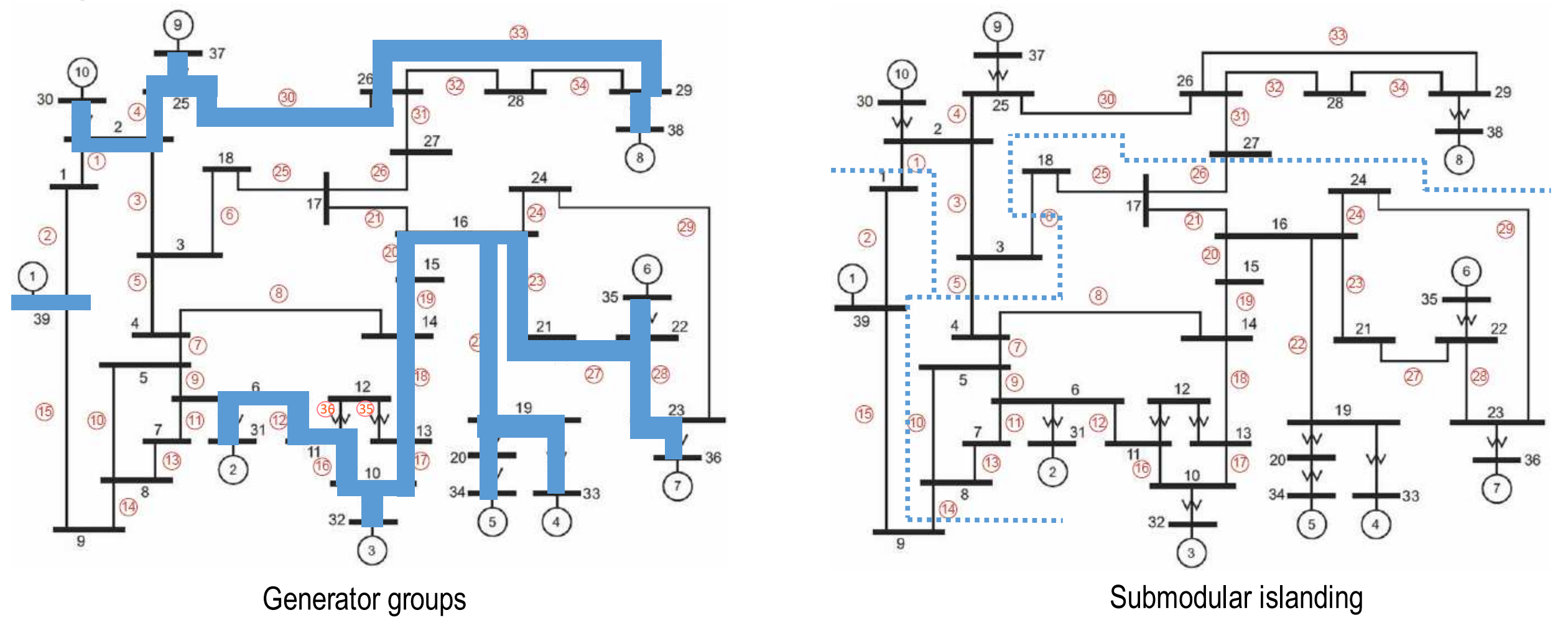
- **Cascading failure:** Following large disturbances, transmission line outages propagate and destabilize entire system
- **Controlled islanding:** Trip a set of transmission lines to partition the system into stable islands
  - Need to separate coherent generators
  - minimize load-generation mismatch



- **We showed:** Selecting transmission lines is a discrete optimization problem
  - Load-generation imbalance is a monotone decreasing function with bounded curvature
  - Separating coherent generators is a matroid constraint
- **Proposed algorithm:**
  - Polynomial-time complexity
  - Provable guarantees on minimal load-generation imbalance



- Simulation study on IEEE 39-bus test case:
- Proposed approach achieves imbalance within a bound of ¼ of the optimal value



Generator groups

Submodular islanding

References

[1] A. Clark, B. Alomair, L. Bushnell, and R. Poovendran. *Submodularity in Dynamics and Control of Networked Systems.* Springer, 2016. ISBN: 3319269755

[2] Z. Liu, A. Clark, P. Lee, L. Bushnell, D. Kirschen, and R. Poovendran, "MinGen: Minimal Generator Selection for Small-Signal Stability in Power Sysems: A Submodular Framework." In 55th IEEE Conference on Decision and Control (CDC), Las Vegas, USA, Dec. 2016.

[3] Z. Liu, Y. Long, A. Clark, P. Lee, L. Bushnell, D. Kirschen, and R. Poovendran, "Minimal Input Selection for Robust Control." In 56th IEEE Conference on Decision and Control (CDC), Melbourne, Australia, Dec. 2017.

[4] Z. Liu, A. Clark, P. Lee, L. Bushnell, D. Kirschen, and R. Poovendran, "A Submodular Optimization Approach to Controlled Islanding under Cascading Failure." In ACM/IEEE International Conference on Cyber-Physical Systems (ICCPS), Pittsburgh, USA, Apr. 2017.

[5] Z. Liu, Y. Long, A. Clark, L. Bushnell, D. Kirschen, and R. Poovendran, "Minimal Input and Output Selection for Stability of Systems with Uncertainties." Under revision to IEEE Transactions on Automatic Control (TAC).

[6] Z. Liu, A. Clark, P. Lee, L. Bushnell, D. Kirschen, and R. Poovendran, "Submodular Optimization for Voltage Control." Under revision to IEEE Transactions on Power Systems (TPS).