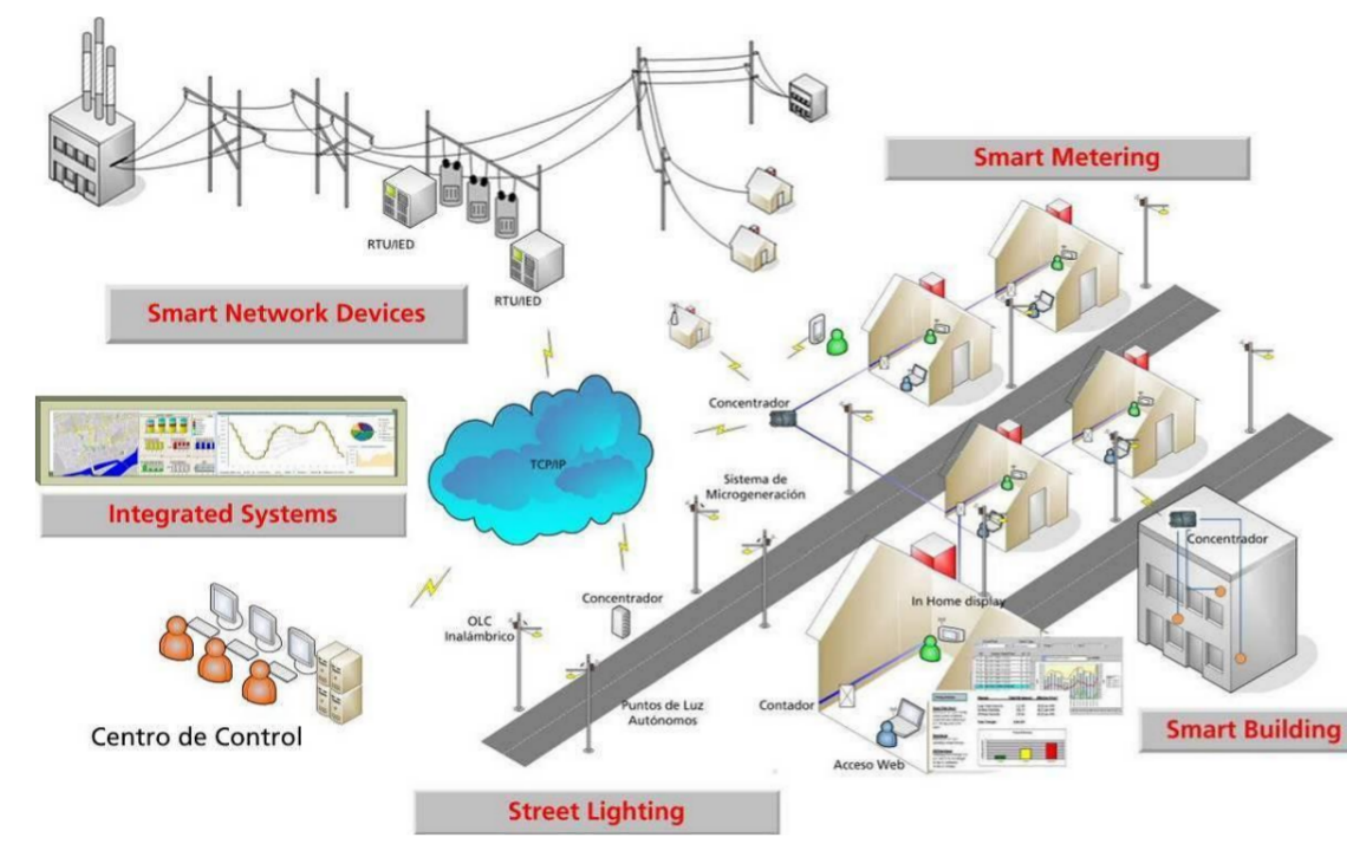


## Control and Stability of the Smart Grid

### Societal-level CPS

- Increasing demand and uncertain renewable power sources
- Multiple entry points for cyber adversaries



### Scientific Questions Addressed

- How to develop 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?

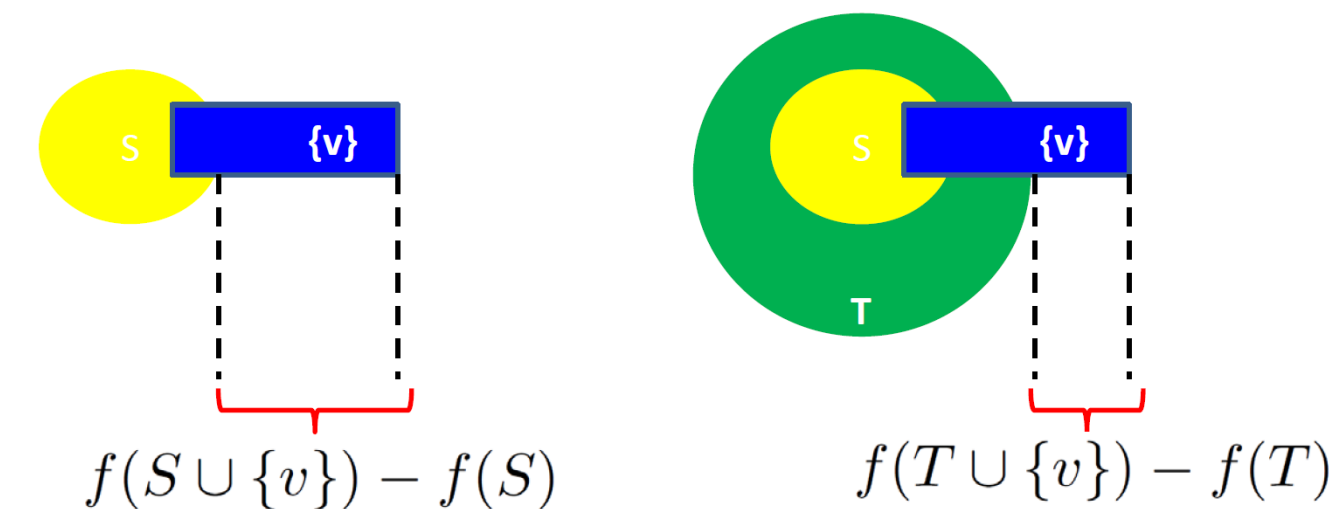
### Submodularity and Bounded Curvature

"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

### Submodular Control Framework

- Combinatorial power system control problems (selecting devices to inject reactive power) in optimization framework
- Optimality guarantees arise from submodularity (voltage stability) and bounded curvature (small-signal & transient stability)
- Verifiable power system stability
- Reduce need for exhaustive search, enable real-time control

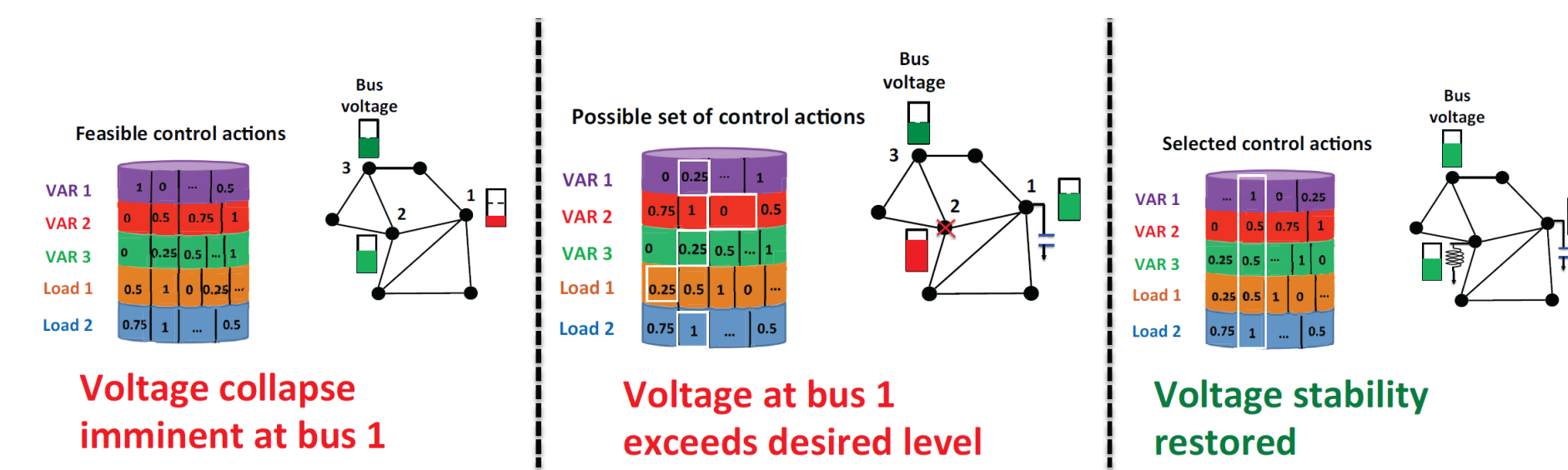
### Intellectual Merit

- 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

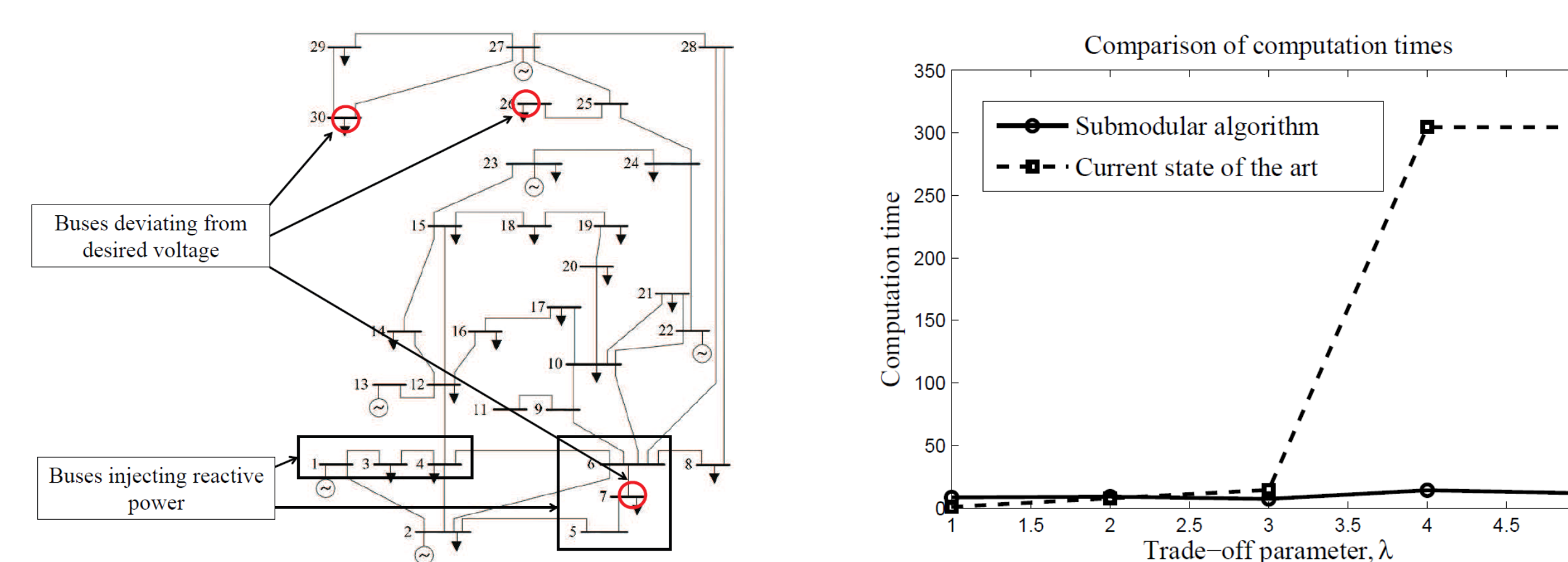
- Improving the stability and reliability of the smart grid and facilitate integration of distributed, renewable energy sources
- Scalable and certifiable control algorithms will have applications to transportation, robotics, and health
- UW graduate-level courses on smart grid resiliency
- Outreach: STEM workshops, UW Math Academy, Ecuador IEEE

## Voltage Stability



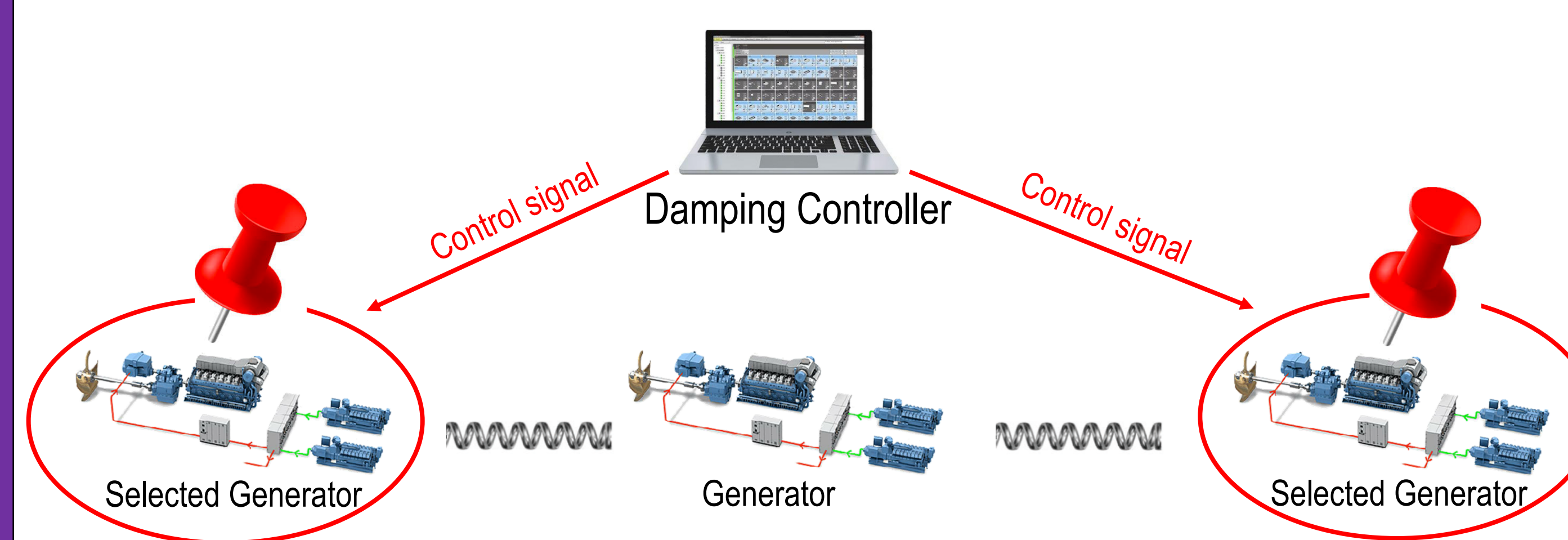
**Voltage stability:** Maintain adequate voltage after disturbance

- Ensured by injecting reactive power
- Which buses should inject reactive power?



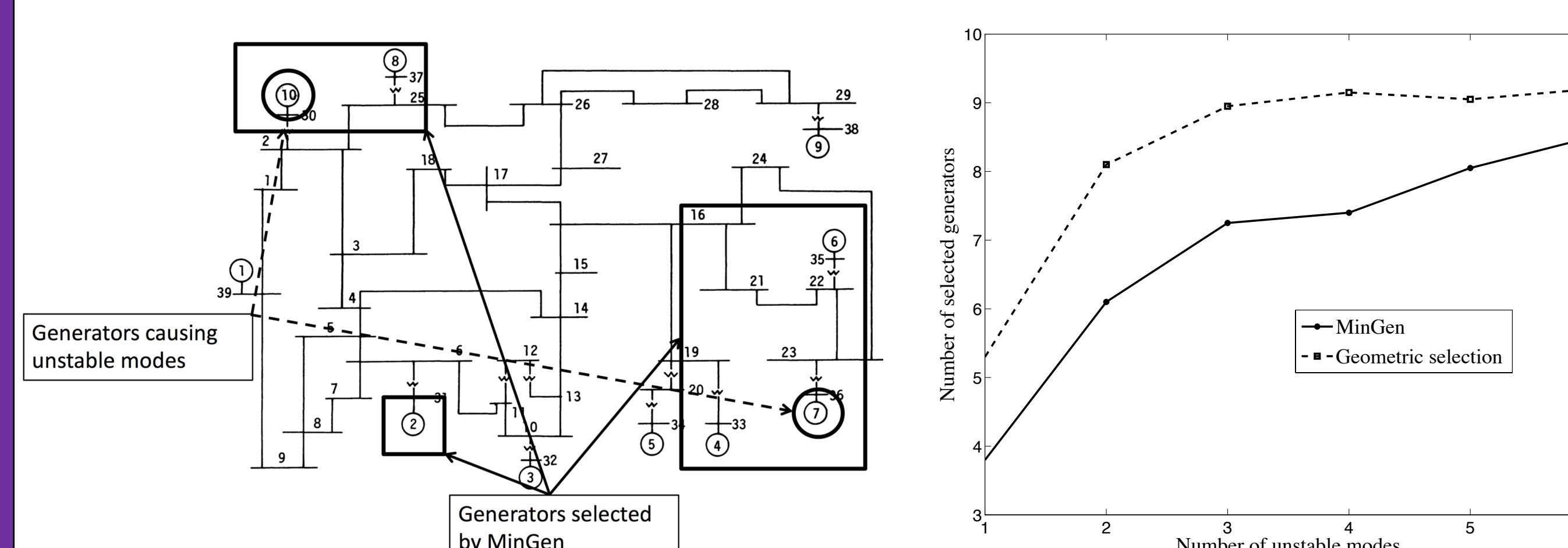
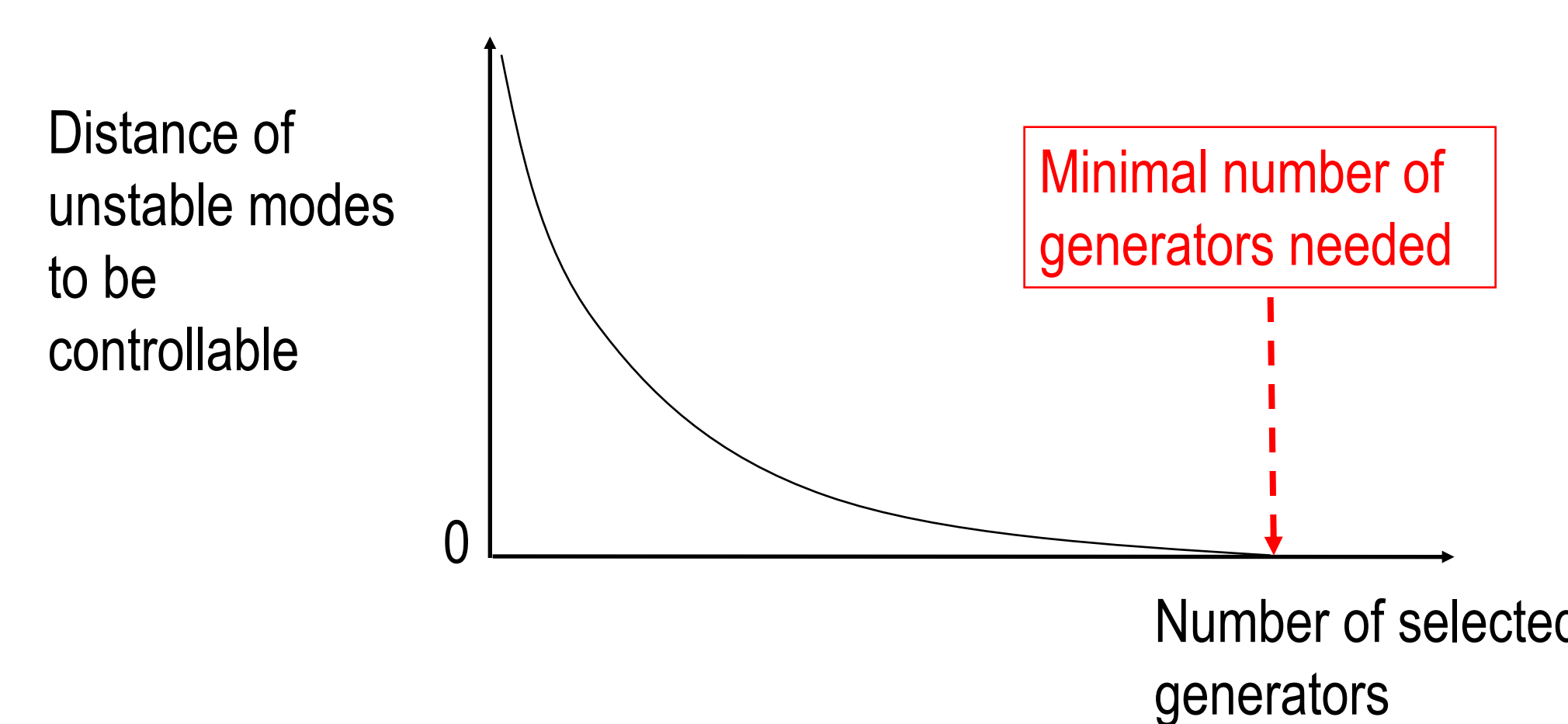
- Algorithms have polynomial complexity (compared to existing exhaustive search algorithms)
- 20 fold reduction in time to compute reaction power injections on IEEE 30-bus network compared to current state of the art

## Small Signal Stability



**Small-signal stability:** Stability of rotor angles after minor disturbances

- Set of generators must exert additional control in order to damp unstable oscillating modes of the system
- Which generators should receive control signal?
- Select a minimal set of generators that satisfy **controllability** and **observability** of unstable modes



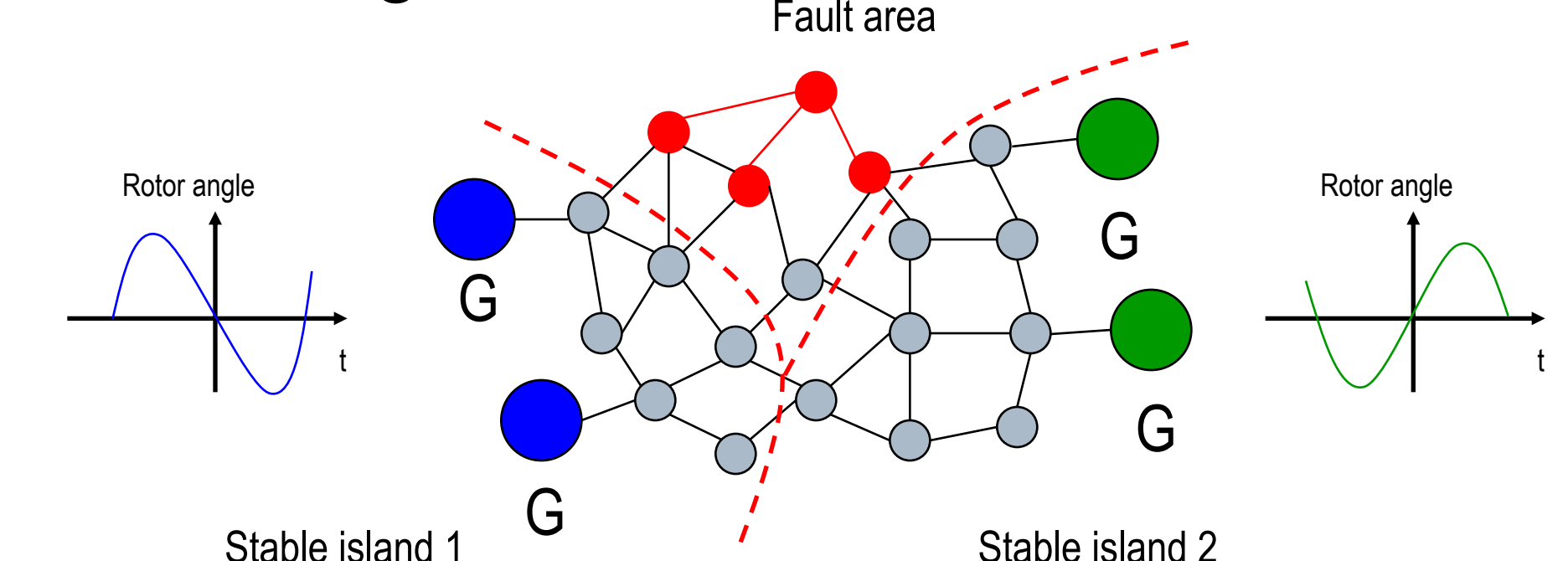
- Submodular optimization technique for selecting generators for damping control in an IEEE 39 bus system
- Significantly reduces the number of generators

## Controlled Islanding for Cascading Failure

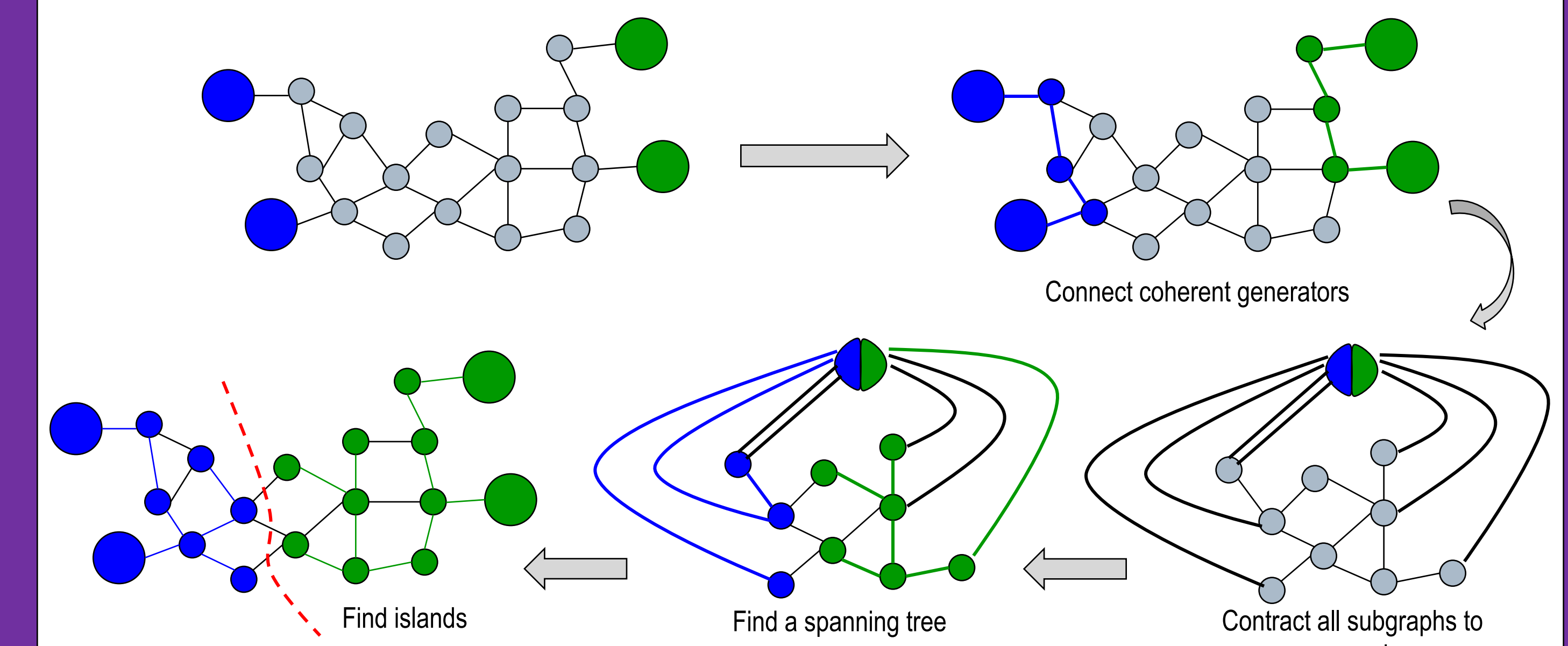
**Cascading failure:** After large disturbances, transmission line outages propagate and destabilize entire system

**Controlled islanding:** Trip transmission lines to partition the system into stable islands

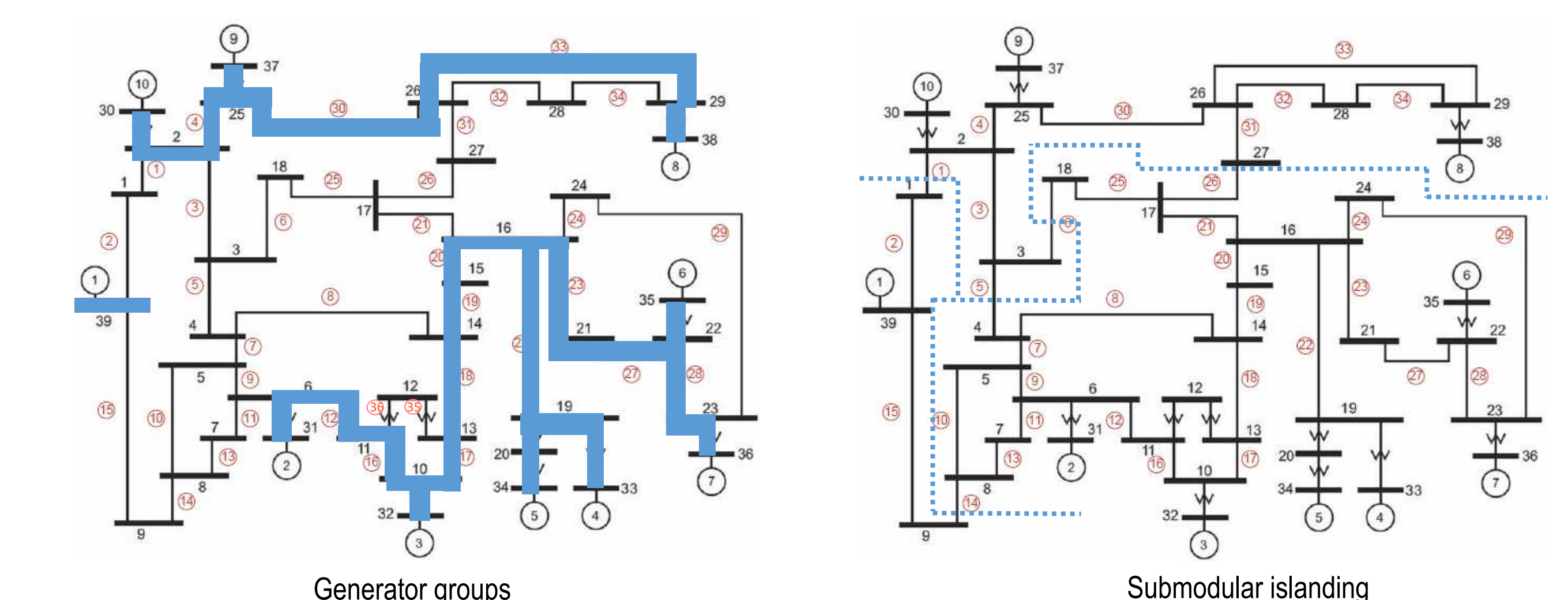
- Separate coherent generators
- Minimize load-generation mismatch



- Select transmission lines to form islands
  - Minimal load-generation imbalance is **monotone decreasing function with bounded submodular ratio**
  - Separating coherent generators is a **matroid constraint**
- Algorithm:
  - Polynomial-time complexity
  - Provable guarantees on minimal load-generation imbalance



- Simulation study on IEEE 39-bus test case
- Minimized generator-load imbalance within 1/4 of the optimal value



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