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

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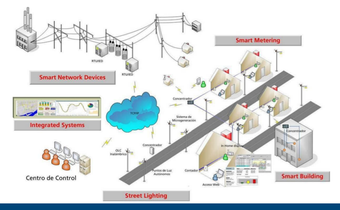
Control and Stability of the Smart Grid

- 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

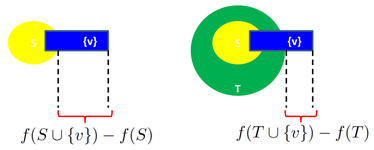
- How to develop smart grid control algorithms with provable stability guarantees?
- How to ensure scalability to large power systems?
- How to provide stability guarantees in the presence of cyber attacks by malicious adversaries?

Submodularity

- "Diminishing returns" property of set functions
- For any sets S⊆T⊆V and v ∈ V\T,

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

- Example: Set cover, f(S) = number of elements in 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 submodular optimization framework
- Optimality guarantees arise from submodular structure, translate to verifiable power system stability
- Reduce the need for exhaustive search algorithms, enable real-time control

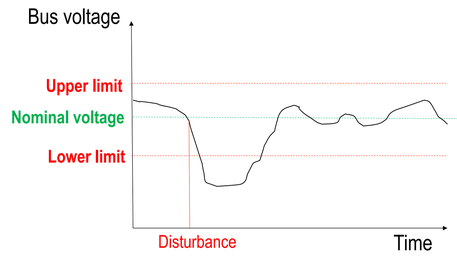
Intellectual Merit

- Identify and exploit inherent submodular 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

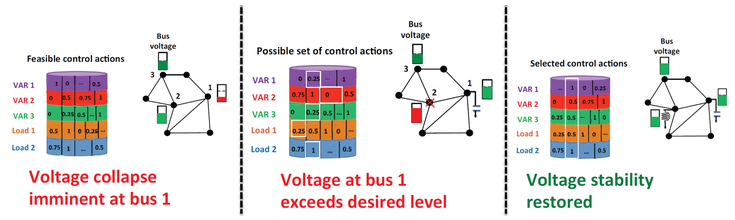
- Improving the stability and reliability of the smart grid and facilitate integration of distributed, renewable energy sources
- Scalable and certifiable control algorithms will have applications to transportation, robotics, and health.
- Graduate-level courses on smart grid security

Thrust 1: Voltage Stability

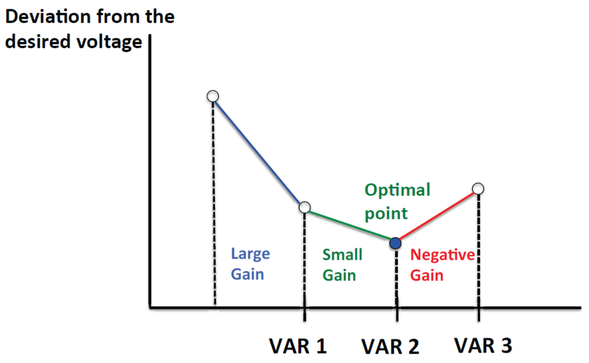


- Voltage stability is the ability of the power system to maintain system voltages following disturbances (e.g., increase in load)
- **Voltage control:** Ensure stability by injecting reactive power at one or more buses

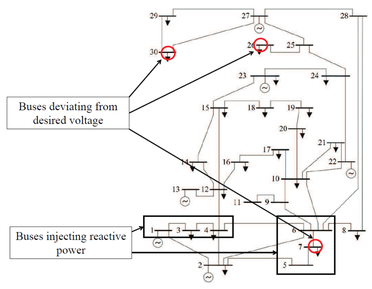
Voltage Stability in Smart Grid

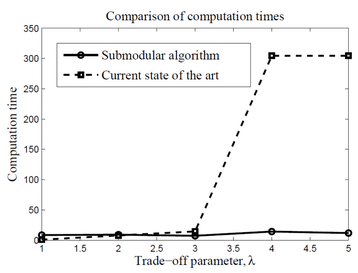


- Injecting reactive power at one bus can cause voltage deviations at neighboring buses
- Selecting which buses should inject reactive power is inherently a combinatorial optimization problem
- Problem formulation: Select a set of buses to inject reactive power that minimize deviation of reactive power and switching cost
- Cost of injecting reactive power: **Supermodular** function of set of devices



- **Proposed algorithms** for general case and case of heavy loading
- Polynomial-time complexity (compared to existing exhaustive search algorithms)

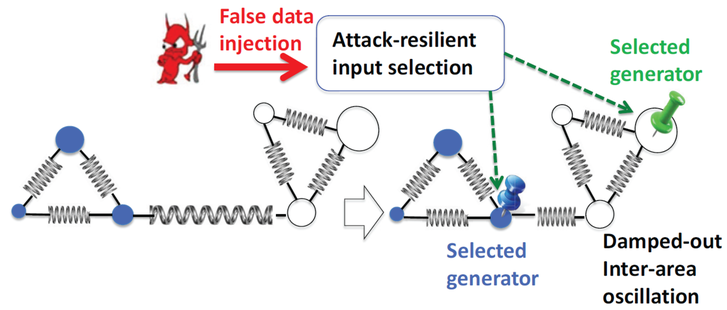




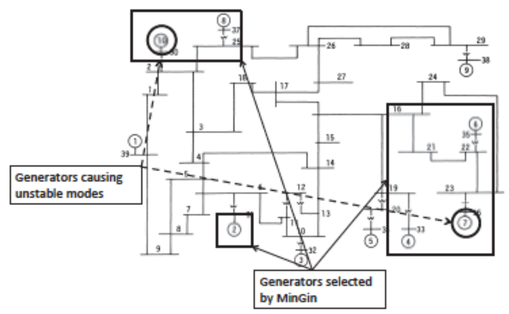
- Simulation study on IEEE 30 bus test case: Submodular approach resolves voltage deviations from desired operating region
- Computation time is significantly reduced

Preliminary Work: Submodular Optimization for 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
- Need to select a set of generators that satisfy **controllability** and **observability** of unstable modes



- **We showed:** Selecting generators to control unstable modes is a submodular optimization problem
- MinGen: Submodular algorithm for minimum-size generator set selection



- Open Problem: Ensuring resilience to cyber attacks

Future Work: Submodular Optimization for Transient Stability

- Transient stability: Ability of power system to recover from major outages (e.g., transmission line tripping)
- One approach: Select a set of transmission lines to cut in order to partition system into internally stable islands
- Which lines to cut: discrete optimization problem
- Need to minimize generator-load imbalance, maximize synchrony of generators

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, "Towards Scalable Voltage Control in Smart Grid: A Submodular Optimization Approach." ACM International Conference on Cyber-Physical Systems (ICCPS), Vienna, Austria, Apr. 2016.

[3] A. Clark, B. Alomair, L. Bushnell, and R. Poovendran, "Input Selection for Disturbance Rejection in Networked Cyber-Physical Systems." In 54th IEEE Conference on Decision and Control (CDC), Osaka, Japan, Dec. 2015.

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

[5] Z. Liu, A. Clark, P. Lee, L. Bushnell, D. Kiirschen, and R. Poovendran, "Submodular Optimization for Voltage Control." Submitted to iEEE Transactions on Power Systems (TPS).