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

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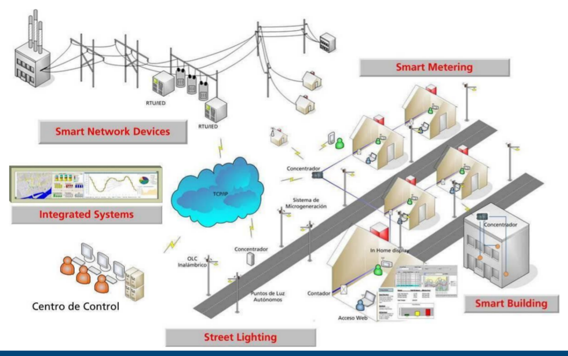
Control and Stability of the Smart Grid

- 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

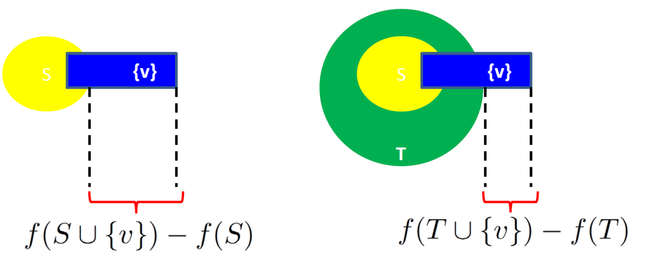
- How to develop smart grid control algorithms with provable stability guarantees?
- How to ensure scalability to large power systems?
- How to provide stability guarantees in the presence of cyber attacks by malicious adversaries?

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

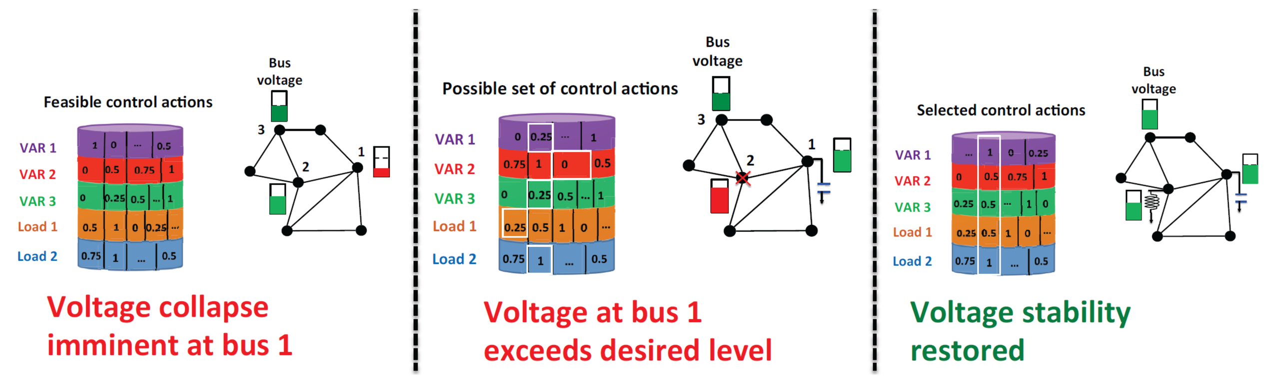
Intellectual Merit

- 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

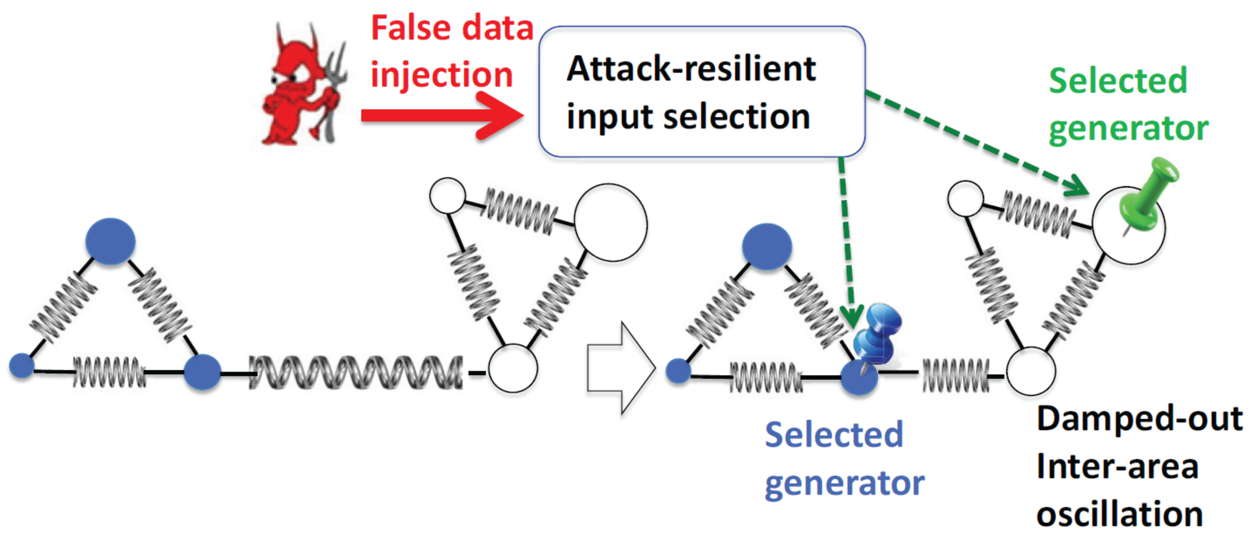
- Improving the stability and reliability of the smart grid and facilitate integration of distributed, renewable energy sources
- Scalable and certifiable control algorithms will have applications to transportation, robotics, and health.
- Graduate-level courses on smart grid security

Thrust 1: Maintaining Voltage Stability



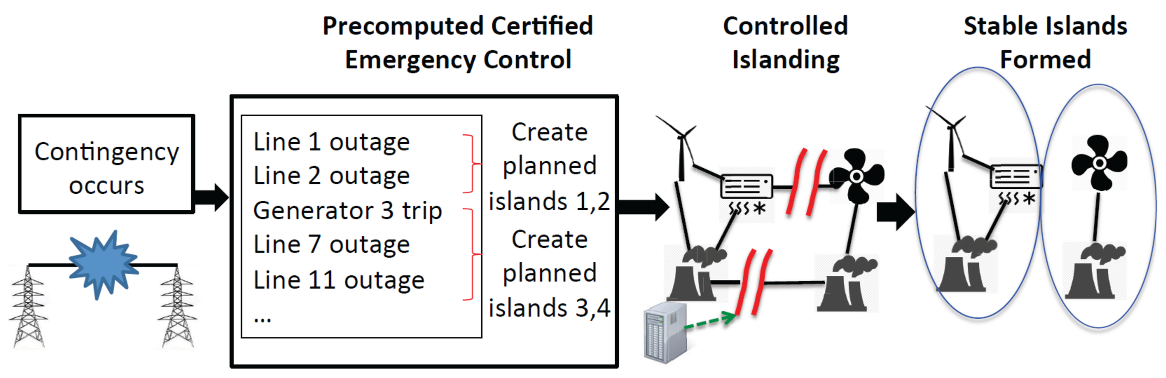
- Voltage stability ensured by injecting reactive power at one or more buses
- Investigate control algorithms based on submodularity of deviation from desired voltage
- Explore distributed algorithms, including mechanisms based on demand response
- New techniques for load control that are resilient to denial-of-service

Thrust 2: Certifiable Online Algorithms for Small-Signal Stability



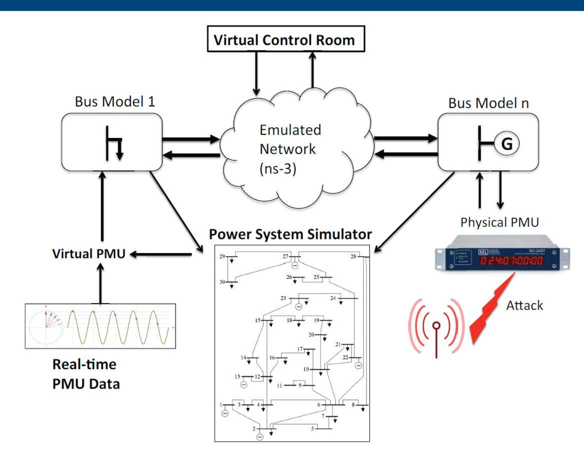
- Small-signal disturbances create oscillations between geographic areas and cause angle separation
- Real-time data from PMUs enable real-time detection of oscillations
- Develop techniques for selecting generators to tamp down oscillations
- Incorporate resilience to disturbances and false data injection

Thrust 3: Certifiable Controlled Islanding for Transient Stability



- Transient instability occurs after major disturbances
- Corrective control must be precomputed
- Submodular optimization approach to choosing internally stable subnetworks for controlled islanding

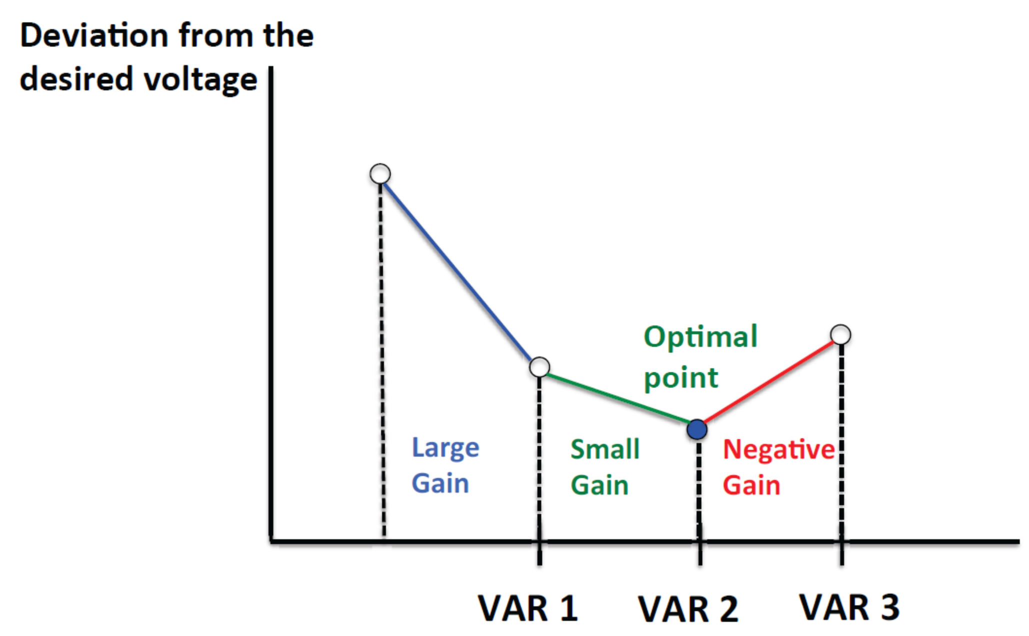
Thrust 4: Testbed Validation and Prototyping



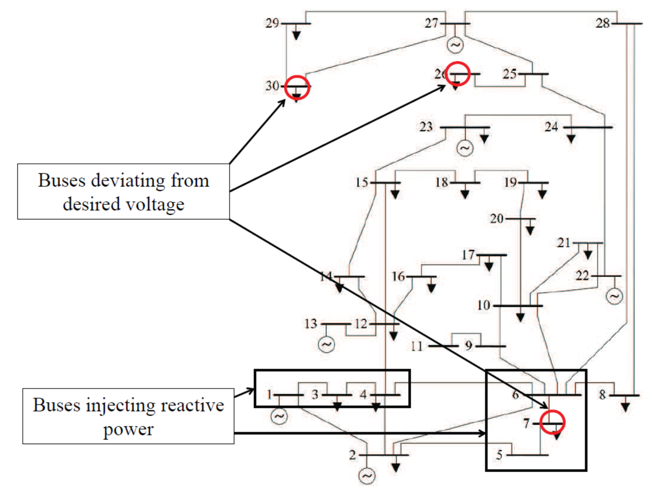
- Implement proposed algorithms in power system simulator
- Integrate with network simulator, real and virtual PMUs

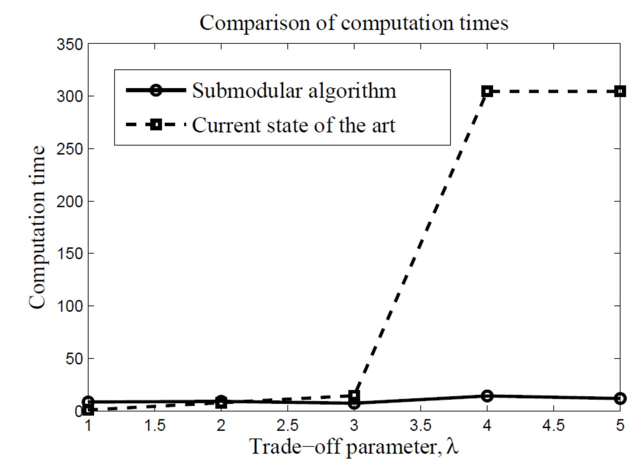
Preliminary Work: Submodular Optimization for Voltage Stability

- Voltage stability caused by insufficient reactive power to meet demand
- Need to decide which buses should inject reactive power (e.g., by switching on capacitor banks) while minimizing switching cost
- Inherently a **combinatorial optimization problem**



- **Problem formulation:** Minimize objective function given by convex function of reactive power deviation and switching cost
- **Proved** that this metric is a supermodular function of the set of devices that inject reactive power
- **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

Future Work: Submodular Optimization for Voltage Stability

- Distributed voltage control algorithms
- Incorporating the impact of adversarial attacks
- Generalized model to incorporate transformer tap changes, reactive power injections by generators
- Include load behavior and control (e.g., demand response) into formulation

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." Submitted to *ACM ICCPS 2016.*

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