Distributed Control of a Swarm of Buildings Connected to a Smart Grid

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Building Energy Control

- Building energy management in smart grid has become an important research area.
- Individual scenarios might include:
  - Demand response
  - Peak power management
  - Demand shifting based on time-of-use pricing and/or renewable energy generation
Distributed Building Control

- Each controller focuses on a single building

- These individual “optimal” controllers create a greedy distributed system.

- This can generate:
  - New peak spikes at non-peak hours
  - Supply-demand imbalances
  - Voltage/frequency instability
Distributed Control Issues

- We need to monitor the system in a holistic way
- Observe and eliminate the discrepancies

Time of Use Pricing – Greedy Distributed Control: Unstable

![Graph showing voltage deviation over time with unstable periods highlighted.](image-url)
Smart Grid Swarm Simulator (S²Sim)

- OpenDSS based grid simulator
- Simulates grid dynamics: power, voltage
- Evaluates and quantifies grid stability
- Enables evaluation of the quality of distributed control of smart buildings
  - Treats each building as a black box
  - Allows co-simulation of individual controllers or data feeds from real-time sensor/actuator systems
**S²Sim Design Overview**

- Communication engine manages external client connections
- OpenDSS engine calculates grid dynamics
- Consumption management engine evaluates power values and sends price feedback
Smart Price Feedback Mechanism

Smart Price Feedback – Greedy Distributed Control: Stable

- $S^2$Sim calculates a price for each client
- Higher deviation $\rightarrow$ Higher price
- Clients reduce their consumption to avoid high prices
Base Model: UCSD Microgrid

UCSD Microgrid
Simplified One-Line Diagram

- 40 MW peak load
- 30 MW Cog-gen
- 1.2 MW solar PV
- 1.8 MW Fuel Cell
- 3.8 Mgal chilled storage
- 10 tons electric chillers
- 5 tons steam chillers

Base Model: UCSD Microgrid

69 kV

12 kV

East Campus Substation

North Campus

IGPP

SIO

3MW

Loads on all feeders
DRs on some feeders

PMU

1 MW each

To campus

From Campus

3.8 Million Gal

4160 V

1 MW each

To campus

Emergency Diesel Generators
Total 3.5
Current System

- Current circuit can support up to 12MW, corresponding to a town with approx. 10000 residents
- A joint effort of six universities
Individual Clients
UCSD/UCB/UPenn/CMU/UMich/Caltech

UCB HVAC
- Flexibility of commercial buildings HVAC system is a significant regulation resource.
- Defined and quantified flexibility of building HVAC systems.
- Designed robust model predictive control framework to guarantee:
  1. Building climate control
  2. Grid flexibility requirements
- Implemented contractual framework for costs and benefits to building and grid.

CMU Scaife Hall
- Sensing and control from 6 building automation systems
- Live data streaming into S$^2$Sim
- Load shedding based on S$^2$Sim pricing signals

UPenn MLE+
- Sheds real-world loads when S$^2$Sim price signal exceeds threshold

UCSD HomeSim
- Residential energy simulation platform
- Can emulate neighborhoods
- Replicated and connected to S$^2$Sim
- Pricing feedback from S$^2$Sim based on consumption, affects appliance rescheduling, battery charge/discharge periods, matching solar energy with demand

Caltech HVAC
- Resistor-capacitor network to model heat transfer
- MPC to satisfy formal specifications in Signal Temporal Logic
\[ \varphi = \Box (\text{occ}_t > 0) \Rightarrow (T_t > T^\text{conf}_t) \]

UMich Beyster Battery Bank
- Proposed Robust model predictive control framework to guarantee:
  1. Building climate control
  2. Grid flexibility requirements
- Proposed contractual framework for costs and benefits to building and grid.
- Flexibility of commercial buildings HV AC system is a significant regulation resource.
- Defined and quantified flexibility in building HV AC systems.
Example Scenario

Step 1: Voltage deviation occurs

- Six individual *smart* building controller
- Sudden power spikes can increase stability, hence price
- Gradual power spikes result in gradual price increase

<table>
<thead>
<tr>
<th>Client Id</th>
<th>Client Name</th>
<th>Client Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>118</td>
<td>UCB1</td>
<td>UCB-CALTECH HVAC Controller</td>
</tr>
<tr>
<td>117</td>
<td>UCSD2</td>
<td>UCSD Medical Facility</td>
</tr>
<tr>
<td>115</td>
<td>UMICH1</td>
<td>Battery Bank Controller</td>
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<tr>
<td>119</td>
<td>UCB2</td>
<td>UCB SDH Hall - Office Building Controller</td>
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<tr>
<td>116</td>
<td>UCSD1</td>
<td>UCSD Campus Dormitory</td>
</tr>
<tr>
<td>120</td>
<td>UPENN1</td>
<td>MLE+ HVAC Controller</td>
</tr>
</tbody>
</table>
Example Scenario
Step 2: Stability is restored

- When consumption decreases, stability is restored
- The price keeps increasing due to high deviation
- After consumption increases again, voltage/price increases
Example Scenario
Step 3: Price reduces

- After a while price starts to reduce
- At the end, the price stabilizes
Next Steps

- Consider the system *twofold*:
  - **Building controllers**: Revise the individual building controllers to account for the grid dynamics
  - **Grid**: Smart grid control instead of individual greedy distributed control

- **Combine** these separate parts to create an optimal close-loop feedback system
  - **Joint optimization** of building savings and grid operation
Summary

- Smart grid energy management is an important topic
  - Residential (house) energy management
  - Building energy management – HVAC in office and commercial buildings
  - Uncoordinated individual control mechanisms can endanger the grid stability
- Distributed energy management in a smart grid
  - \textbf{S}²\textbf{Sim}: Simulates grid dynamics; evaluates and quantifies grid stability
  - Created a realistic grid model, corresponding to a small town
  - Monitor and prevent instability events
  - Devised a smart price feedback mechanism