Robust Control of Residential Demand Response Network with Low Bandwidth Input

2008 ASME Dynamic Systems and Controls Conference

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October 21, 2008

Motivation

We don't generate enough power!

- "Flex your power" Days
- Brown-outs
- Rolling blackouts

Peak Power is Dirty and Expensive!

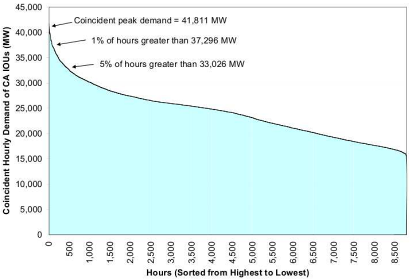
- Peaker Plants
- Pollution
- Carbon Emissions

Global Problem

- China
- South Africa
- United States

Overall Goal: Reduce the peak power

2004 Load Duration for CA IOU



Flex your POWER SM

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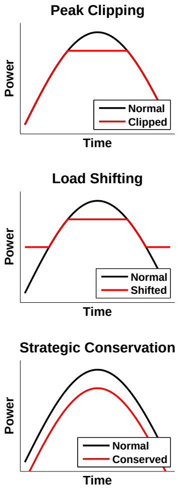
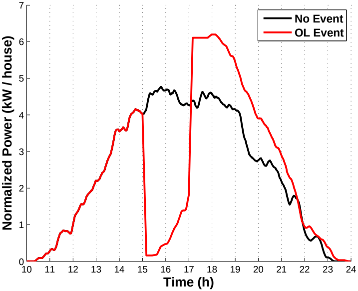
Load Management Background

- LM Goal:
  - Manipulate power demand on the electrical distribution and generation system.
- LM Types [Bellarmine, 2000]:
  - Peak Clipping
  - Load Shifting
  - Strategic Conservation
- Reasons to use LM:
  - Avoid blackouts
  - Avoid peaker plants
- Examples Technologies:
  - Load Switches
  - Grid Friendly Appliances [Lu and Nguyen, 2006].
  - AutoDR [Watson et al., 2004].



Load Management Control

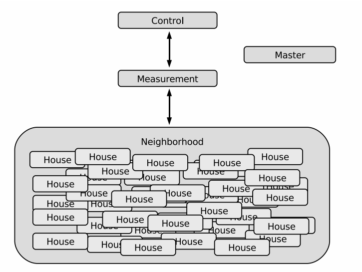
- LM controls problem
    - Systemic Control
    - Local Control
    - Disturbances
- State of the Art
    - Most often open loop
        - Thermostat setback events e.g. $4^o F$ for 2 hours
        - Load switch profiles [NavidAzarbaijani and Banakar, 1996]
        - Day ahead pricing
    - Some feedback control
        - Model predictive control [Huang et al., 2004]
        - Agents [Lum et al., 2005]



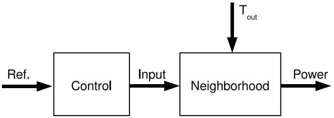
Problem Approach

- Restrict scope
  - Residential HVAC (Easily Expanded)
  - Inexpensive Equipment (PCT)
- Use Complex Simulation as Plant
  - Thermal Simulation of Individual Houses
  - Design Price Responsive Thermostat
  - Simulate Thermostat in Each House
  - Randomize House/Thermostat Parameters
  - Examine Aggregate Response
- Design Robust Controller for Plant

Systemic Simulation Task Diagram



Systemic Simulation Block Diagram



Design Approach

Goal: Control system power

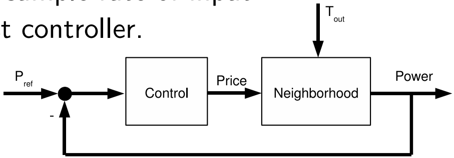
- Peak Clipping
- Reference Following

Design Challenges

- Very high order – 5000 States
- Nonlinear – nonlinear regulators in loop
- Stochastic – each house different/random
- Slow Actuator – 15 minute update time

Design Methodology

1. Identify as low order linear system.
2. Discretize at sample rate of input.
3. Design robust controller.

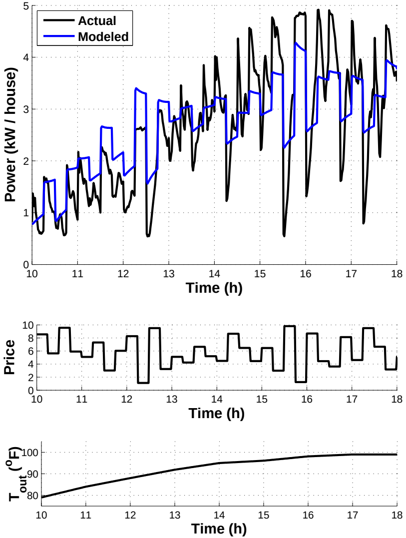


T_{out}
P_{ref}
Control
Price
Neighborhood
Power
-

System Identification

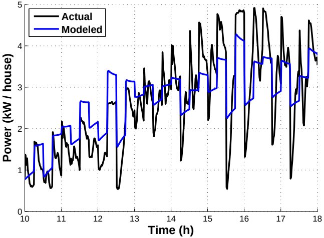
- Model Definition
  - Output: Power
  - Input: Price
  - Disturbance Input: T_{out}
- Second Order ARX
  - Whitest Residual
  - Best Trade-off
- Large Errors Due To:
  - Unknown Disturbances
  - Non-linearities (e.g. Saturation)

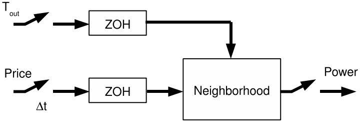
$$\hat{P}(z) = \frac{-0.2016z + 0.1923}{z^2 - 0.9771z + 0.0387} C(z) - \frac{0.213z - 0.2063}{z^2 - 0.9771z + 0.0387} T_{out}(z)$$



Discretize At Input Sample Rate

- Input Sample Rate 15min
  - Communications Constraints
  - FM Carrier (300 bps)
- Why not use 15min for ID?
  - Allows Flexibility in Design
  - Faster Communications = Faster Control





$$\hat{P}(k) = C\hat{X}(k)$$

$$\hat{X}(k+1) = \hat{A}\hat{X}(k) + \hat{B}U(k)$$

$$\hat{X}(k) = \begin{bmatrix} \hat{X}_T(k) & \hat{X}_C(k) \end{bmatrix}^T ; \hat{X}_T, \hat{X}_C \in \Re^2$$

$$U = \begin{bmatrix} T_{out} & C_{ost} \end{bmatrix}$$

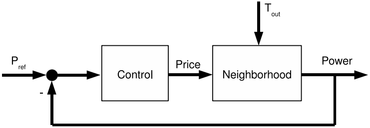
$$\hat{A} = \begin{bmatrix} \hat{A}_T & 0 \\ 0 & \hat{A}_C \end{bmatrix} ; \hat{A}_T, \hat{A}_C \in \Re^{2x2}$$

$$\hat{B} = \begin{bmatrix} \hat{B}_T & \hat{B}_C \end{bmatrix} ; \hat{B}_T, \hat{B}_C \in \Re^{4x1}$$

$$C = \begin{bmatrix} 1 & 0 & 1 & 0 \end{bmatrix}$$

Robust Controller Synthesis

- Sliding Mode Control
  - Tracking Performance
  - Robustness to modelling errors
- Ignore uncertainties
  - Proof of concept
  - Bounds arbitrary anyway
- Must use output feedback
  - Extend state space (ζ)
  - Fictitious input $r(k)$



System Equations

$$P(k) = P_C(k) + d_T(k) + d_{un}(k)$$

$$P_C(k) = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} X_C(k) \\ \zeta(k) \end{bmatrix}$$

$$\begin{bmatrix} X_C(k+1) \\ \zeta(k+1) \end{bmatrix} = \begin{bmatrix} \hat{A}_C & \hat{B}_C \\ 0 & \tau \end{bmatrix} \begin{bmatrix} X_C(k) \\ \zeta(k) \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} r(k)$$

$$d_T(k) = \begin{bmatrix} 1 & 0 \end{bmatrix} X_T(k)$$

$$X_T(k+1) = \hat{A}_T X_T(k) + \hat{B}_T T_{out}(k)$$

Sliding Variables

$$\epsilon(k) = P(k) - P_{ref}(k)$$

$$S(k) = \epsilon(k+1) - \lambda \epsilon(k)$$

$$|S(k+1)| < |S(k)|$$

Control Law

$$r(k+1) = -\frac{1}{h(k+1)} \Big(f(k+1) + d(k+2) - P_{ref}(k+2)$$

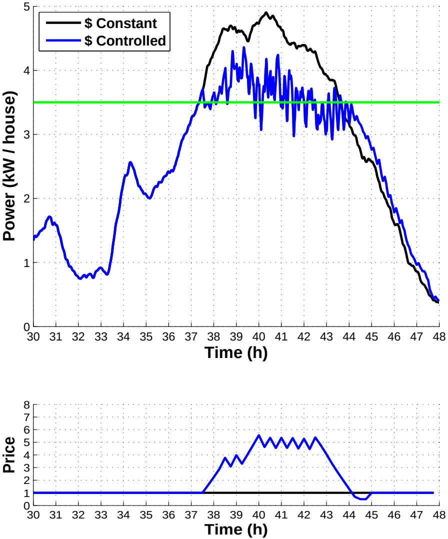
$$- (1+\lambda)\epsilon(k+1) + \lambda\epsilon(k) + \phi \operatorname{sgn}(s) \Big)$$

$$h(k+1) = B_{C(1)}$$

$$f(k+1) = A_{C(1,1)} X_{C(1)}(k+1) + A_{C(1,2)} X_{C(2)}(k+1) + B_{C(1)} \tau \zeta(k)$$

Sliding Control Results

- 3.5kWn Reference
- Good Performance
    - "Chattering" Natural
    - Overshoot
    - Parameter Bounds



Wrap-up

- Conclusions
  - Methodology works
  - Closed Loop Systemic Control
- Future Work
  - Obtain robustness bounds
  - Examine other control types

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