Set Point Control of a Thermal Load Population

CE 291F Final Project

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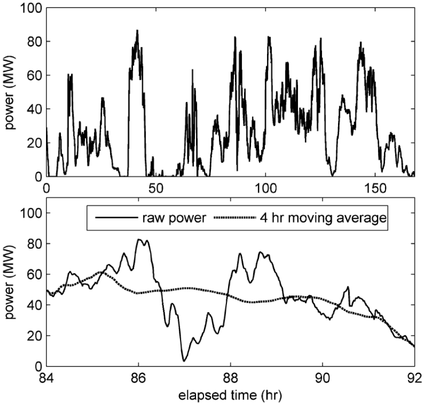
Motivation

- Buildings responsible for 40% of energy consumption
- Renewable electricity generation is intermittent
- Large-scale storage is not feasible, so supply must match demand at each time instant



Background

- residential energy use primarily due to thermostatiscally controlled loads (TCL)
- typical TCLs: HVAC, water heater, refrigerator
- for a single TCL, state variables are temperature of load and position of thermostat (on/off)

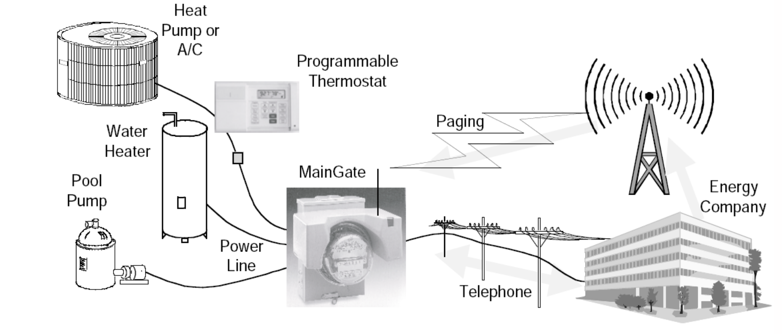


Figure B-3. MainGate System Overview

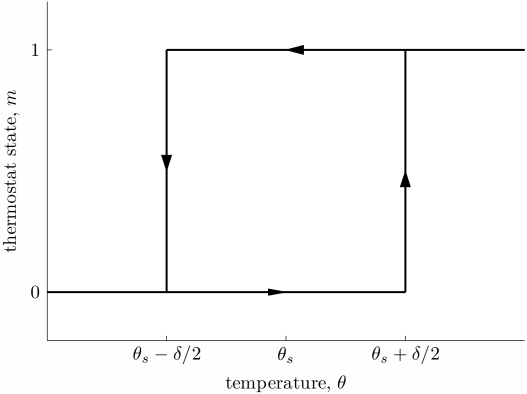
Strategy

- Renewable generation (e.g., wind power) has high- and low-frequency components
- Match low-frequency with slower conventional generation (e.g., coal, nuclear, natural gas)
- Match high-frequency (sub 4-hour) using thermal loads
- Analogy between energy storage using batteries (electrical capacitance) and controlling TCLs (thermal capacitance)

Nonlinear Thermostat Behavior

- most TCLs use nonlinear hysteresis control

$$m_{t_{n+1}} = \begin{cases} 0, & \theta_{t_n} < \theta_s - \delta/2 \\ 1, & \theta_{t_n} > \theta_s + \delta/2 \\ m_{t_n}, & otherwise \end{cases}$$



Thermostat Actuation, $\theta_s \rightarrow \theta_s + u_{t_n}$

$$m_{t_{n+1}} = \begin{cases} 0, & \theta_{t_n} < \theta_s - \delta/2 + u_{t_n} \\ 1, & \theta_{t_n} > \theta_s + \delta/2 + u_{t_n} \\ m_{t_n}, & \textit{otherwise} \end{cases}$$

- Previous work focuses on directly interrupting power
- Recently, programmable communicating thermostats (PCT) are more widely available
- Set point changes should be small, so that customer comfort is maintained
- Small set point changes mean only loads that were close to edge of deadband are turned on/off

Thermal Load Dynamics

$$\theta_{t_{n+1}} = a\theta_{t_n} + (1-a)(\theta_a - mRP) + w_{t_n}$$

- temperature of load, θ
- ambient temperature, θ_a
- thermostat state, m
- energy transfer rate, P
- thermal resistance, R
- thermal capacitance, C
- thermal mass constant, $a = exp(-h/CR)$
- time step, $h = t_{n+1} - t_n$
- process noise, $w_{t_n} \sim N(0, h\sigma^2)$

Aggregated Power Demand

$$y_{t_{n+1}} = \sum_{i=1}^{N} \frac{1}{\eta_i} P_i m_{i,t_{n+1}}$$

- load index, i
- number of loads in population, N
- thermostat state, m
- energy transfer rate, P
- energy transfer efficiency, η
- power demand from entire population, y

Solution of Theoretical Model

- Load populations are very large, so realizing every state is not tractable
- Instead, propogate the probability distribution of loads at each temperature
  - Assume load population is homogeneous
  - Formulate Coupled Fokker-Planck Equations (CFPE)
  - Boundary conditions ensure conservation of proability
  - Compute steady-state solution
- Result is a linear model (aggregation of nonlinear models is linear)

$$\Delta y_{t_{n+1}} = -\frac{\Delta u_{t_n}}{\delta} \sum_i \frac{1}{\eta_i} P_i + e_{t_n}$$

System Identification

- Linear model is justified on physical grounds
- Fine-tune the physical model using ARMAX model

$$A(q)y_{t_n} = B(q)u_{t_n} + C(q)e_{t_n}$$

- Choose parameters to minimize prediction error
- Determine coefficients by learning from data

$$A(q) = 1 - a_1 q^{-1}$$

$$B(q) = b_1 q^{-1} + b_2 q^{-2}$$

$$C(q) = 1 + c_1 q^{-1} + c_2 q^{-2} + \cdots + c_8 q^{-8}$$

Load Population Heterogeneity

- Exact solution applies only to homogeneous loads
- In reality, loads are highly heterogeneous
- As load heterogeneity increases, System ID model outperforms theoretical model

Controller Design

- Choose control law such that output variance is minimized

$$\min_{u_{t_n}} E[y_{t_n}^2]$$

- Control takes effect one time step later

$$u_{t_n} = \frac{C(q)\tilde{y}_{t_{n+1}} - \frac{C(q)-A(q)}{q^{-1}} y_{t_n}}{B(q)}$$

- Controller requires prediction, $\tilde{y}_{t_{n+1}}$ at time t_n
- If control takes immediate effect, prediction is unnecessary

Simulation Results

Future Work

- Finish simulations
- Evaluate controller performance
    - How well does demand match supply? (energy savings)
    - Following electrical capacitance analogy, how big is the "battery"?
    - Compare against other controllers (sliding mode control)
- Relax modeling assumptions
    - Ambient temperature constant in time, and over population
    - Is required information available in reality?
    - Is the control value discretized? Is it delayed in time?

The End

Questions?
Comments?

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