Controller and System Design for HVAC Systems with Thermal Energy Storage

David I. Mendoza-Serrano and Donald J. Chmielewski
Illinois Institute of Technology

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Outline

• Motivation and Objective
• Market Responsive Control
• Equipment Design with Embedded MRC
• Case Study
Power System Reliability

Power Produced \[\rightleftharpoons\] Power Consumed

![Power Produced Graph]

\[\text{MW}\]

\[\text{Days}\]

\[\text{MW}\]

\[\text{Days}\]
Overview of Smart Grid

Generators

Transmission

Consumer Demand

Generator Dispatch

Renewable with Storage

Smart Homes

Smart Manufacturing

Commercial Buildings
Cooling Power Consumption

Cooling is mainly required during the hottest times of a day...

Outside Temperature.
Correlation Between Cooling Loads and Energy Prices

August 3 - 6, 2001.
Pittsburg, PA.
Traditional HVAC System

- Heat is removed from the building by a chiller
- Chiller consumes electric power
- Assume real-time prices for electricity
Thermal Energy Storage

TES helps time shift electricity consumption to periods of low electricity prices.
HVAC System with TES

- Building heat can be sent to chiller or TES
- Heat must eventually be removed from TES by chiller.
Impact of TES
Impact of Larger TES

Heat from Environment → Building → Heat from Building → Heat to Chiller → Chiller → Power Consumption

Thermal Energy Storage

Heat from Environment → Building → Heat from Building → Heat to Chiller → Chiller → Power Consumption

Thermal Energy Storage

Chiller Cooling Load (Qc)
Time (days)
Heat Flow (KW)

Qc
Qr

Heat Flow (KW)
23 24 25 26
200
300
400
500
600

Time (days)
HVAC Design Questions

• What are the energy expenditures?

• What is the appropriate size of the TES?

• Is there a benefit to changing chiller size?
Outline

• Motivation

• Market Responsive Control

• Equipment Design with Embedded MRC

• Case Study
Building Example

Outside Environment ($T_3$)

Walls

Room

Room

Room

Room

Windows

Outside Environment ($T_3$)
Building Model

Air Temperature

\[ \dot{T}_o = \frac{K_{11}A_1(T_{11} - T_o) + K_{21}A_2(T_{21} - T_o) - Q_c}{\rho_o C_{p0} V_o} \]

Wall Layers

\[ \dot{T}_{11} = \frac{K_{11}(T_o - T_{11}) - K_{12}(T_{11} - T_{12})}{\rho_1 C_{p1} \Delta x_1} \]
\[ \dot{T}_{12} = \frac{2K_{12}(T_{11} - T_{12})}{\rho_1 C_{p1} \Delta x_1} \]

Window Layer

\[ \dot{T}_{21} = \frac{K_{22}(T_3 - T_{21}) + K_{21}(T_o - T_{21})}{\rho_2 C_{p2} \Delta x_2} \]
Building Operation

Disturbance \( \rightarrow T_3 = 32C \pm 4C \)

Comfort Constraints \( \rightarrow T_o^{\text{min}} \leq T_o \leq T_o^{\text{max}} \)

Manipulated Variable \( \rightarrow 0 \leq Q_c \leq Q_c^{\text{max}} \text{ (kW}_T) \)

Power Usage \( \rightarrow P_c \leq \beta Q_c \text{ (kW}_e) \)

Energy Cost \( \rightarrow C_e \text{ ($/kW}_e\text{hr}) \)

Instantaneous Expenditures \( \rightarrow R = C_e P_c \text{ ($/hr)} \)
Building Model with TES

Air Temperature

\[ \dot{T}_o = \frac{K_{11}A_1(T_{11} - T_o) + K_{21}A_2(T_{21} - T_o) - Q_o - Q_s}{\rho_o C_p 0 V_o} \]

Wall Layers

\[ \dot{T}_{11} = \frac{K_{11}(T_o - T_{11}) - K_{12}(T_{11} - T_{12})}{\rho_1 C_{p1} \Delta x_1} \]

\[ \dot{T}_{12} = \frac{2K_{12}(T_{11} - T_{12})}{\rho_1 C_{p1} \Delta x_1} \]

Window Layer

\[ \dot{T}_{21} = \frac{K_{22}(T_3 - T_{21}) + K_{21}(T_o - T_{21})}{\rho_2 C_{p2} \Delta x_2} \]

Energy in Storage

\[ \dot{E}_s = Q_s \]
Building Operation with TES

Manipulated Variables \[ 0 \leq Q_c \leq Q_{c}^{\text{max}} \]
\[ Q_{s}^{\text{min}} \leq Q_s \leq Q_{s}^{\text{max}} \]

Equipment Constraints \[ 0 \leq E_s \leq E_{s}^{\text{max}} \]
\[ Q_R = Q_c + Q_s \geq 0 \]
Outside Temperature Model

$W$ \hspace{1cm} \text{White Noise Input} \quad \rightarrow \quad \text{Shaping Filter} \quad \rightarrow \quad \text{Sequence with Outside Temperature Characteristics} \quad T_3
Outside Temperature Spectral Density

\[ W \xrightarrow{\text{White Noise Input}} \text{Shaping Filter} \xrightarrow{\text{Sequence with Outside Temperature Characteristics}} T_3 \]

![Graph showing the spectral density of outside temperature characteristics](image)

- **Spectral Density ($$/MW^2/hr) vs. Frequency (rad/hr)**
  - Spectral Density ranges from $10^{-3}$ to $10^4$
  - Frequency ranges from $10^{-3}$ to $10^1$
Outside Temperature Realization

\[ W \rightarrow \text{Shaping Filter} \rightarrow \text{Sequence with Outside Temperature Characteristics} \]

- White Noise Input
- Sequence with Outside Temperature Characteristics

Graph showing outside temperature over time, with values ranging from 26°C to 38°C.
Outside Temperature Model

\[ T_3 = e_1 + \bar{T}_3 \]
\[ \dot{e}_1 = e_2 \]
\[ \dot{e}_2 = -\omega_c^2 e_1 - 2\chi \omega_c e_2 + \omega_c^2 (w - e_3) \]
\[ \dot{e}_3 = (w - e_3) / \tau_h \]

where:
\[ \omega_c = \frac{2\pi}{\tau_c} \]
\[ \tau_c = 24 \text{ hr} \]
\[ \tau_h = 1 \text{ hr} \]
\[ \chi = 0.1 \]
\[ S_w = \left( \frac{4\chi}{\omega_c} \right) \left( \frac{\omega_c^2 \tau_h^2 + 2\chi \omega_c \tau_h + 1}{\omega_c^2 \tau_h^2} \right) \Sigma T_3 \]
\[ \Sigma T_3 = (4K)^2 \]
Deviation Variables

\[ x = [T_o - \overline{T}_o \quad T_{11} - \overline{T}_{11} \quad T_{12} - \overline{T}_{12} \quad T_{21} - \overline{T}_{21} ] \]

\[ E_s - \overline{E}_s \quad e_1 \quad e_2 \quad e_3 ]^T \]

\[ u = [Q_s - \overline{Q}_s \quad Q_c - \overline{Q}_c ]^T \]

\[ z = [T_o - \overline{T}_o \quad E_s - \overline{E}_s \quad Q_c - \overline{Q}_c \quad Q_R - \overline{Q}_R ]^T \]

\[ \dot{x} = Ax + Bu + Gw \]

\[ z = Dx + Du \]

\[ z_{\text{min}} \leq z \leq z_{\text{max}} \]
Stochastic Analysis

\[ \dot{x} = Ax + Bu + Gw \]

\[ z = D_x x + D_u u \]

\[ u = Lx \]

\[ 0 = (A + BL)\Sigma_x + \Sigma_x (A + BL)^T + GS_w G^T \]

\[ \zeta_j = \rho_j (D_x + D_u L)\Sigma_x (D_x + D_u L)^T \rho_j^T \]

\[ \sigma_j = \sqrt{\zeta_j} \]

\[ (\rho_j = j^{th} \text{ row } I) \]
\[ \dot{x} = Ax + Bu + Gw \]
\[ z = D_x x + D_u u \]
\[ u = Lx \]

Find \( L \) such that
\[
0 = (A + BL)\Sigma_x + \Sigma_x (A + BL)^T + G S_w G^T
\]
\[
\zeta_j = \rho_j (D_x + D_u L)\Sigma_x (D_x + D_u L)^T \rho_j^T
\]
\[
\sigma_j = \sqrt{\zeta_j}
\]

\[ 2\sigma_j < z_j^{\max} \quad \text{and} \quad 2\sigma_j < -z_j^{\min}, \quad j = 1 \ldots n_z \]
Stochastic Control

- Heat from Environment
- Heat from Building
- Heat to Chiller
- Heat to TES
- Power Consumption
- Chiller
- Building
- Thermal Energy Storage

Heat Flow (KW)

Time (days)

23 24 25 26

200
300
400
500
600

Chiller Cooling Load (Qc)

Heat Flow (KW)
Expenditures

Instantaneous Expenditures

\[ R = C_e P_c \]

Average Expenditures

\[
\bar{R} = \lim_{T \to \infty} \left\{ \frac{1}{T} \int_0^T C_e P_c \, dt \right\} \\
= E[C_e P_c]
\]
Economic MPC

Minimize Expenditures over Horizon T

\[ \overline{R} \approx \frac{1}{T} \int_{0}^{T} C_e P_c dt \]

• Braun, 1992
• Morris et al., 1994
• Kintner-Meyer and Emery, 1995
• Henze et al., 2003
• Oldewurtel et al, 2010
• Ma et al, 2012
Market Responsive Control

\[
\bar{R} = E[C_e P_c]
\]
Market Responsive Control

\[
\overline{R} = E[C_e P_c]
\]

Enforce the condition: \[
\tilde{P}_c = \alpha_1 \tilde{C}_e + \alpha_2 \tilde{B}_e
\]

where: \[
\tilde{P}_c = P_c - \overline{P}_c \quad \text{and} \quad E[\tilde{C}_e \tilde{B}_e] = 0
\]

\[
\tilde{C}_e = C_e - \overline{C}_e
\]
Market Responsive Control

\[ \bar{R} = E[C_e P_c] \]

Enforce the condition:

\[ \tilde{P}_c = \alpha_1 \tilde{C}_e + \alpha_2 \tilde{B}_e \]

where:

\[ \tilde{P}_c = P_c - \bar{P}_c \]

\[ \tilde{C}_e = C_e - \bar{C}_e \]

and

\[ E[\tilde{C}_e \tilde{B}_e] = 0 \]

Then:

\[ \bar{R} = E[\tilde{C}_e \tilde{P}_c] + \bar{C}_e \bar{P}_c \]

\[ = E[\alpha_1 \tilde{C}_e^2] + \bar{C}_e \bar{P}_c \]

\[ = \alpha_1 \Sigma_{C_e} + \bar{C}_e \bar{P}_c \]
Electricity Price

\[ W \rightarrow \text{Shaping Filter} \rightarrow \int \rightarrow K \rightarrow \tilde{T}_3 \rightarrow \tilde{C}_e \]
Orthogonal to Electricity Cost

\[ W \rightarrow \text{Shaping Filter} \rightarrow \int \rightarrow K \rightarrow \tilde{T}_3 \rightarrow \tilde{C}_e \rightarrow \int \rightarrow \tilde{B}_e \]
Disturbance Scaling

\[ W \rightarrow \text{SF1} \rightarrow \text{SF2} \rightarrow \text{SF3} \rightarrow \tilde{T}_3 \]

\[ \alpha_1 \rightarrow \text{SF2} \rightarrow \tilde{C}_e \]

\[ \alpha_2 \rightarrow \text{SF3} \rightarrow \tilde{B}_e \]

\[ \dot{x} = Ax + Bu + Gw \quad \quad G = (G_0 + \alpha_1 G_1 + \alpha_2 G_2) \]
Market Responsive Control

\[
\min_{L, \Sigma_x \geq 0, \zeta_j, \sigma_j, \alpha_1, \alpha_2} \left\{ \alpha_1 \Sigma_{Ce} + \overline{C}_e \overline{P}_c \right\}
\]
\[
\text{s.t.}
\]
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0 = (A + BL)\Sigma_x + \Sigma_x (A + BL)^T + GS_w G^T
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2\sigma_j < z_j^{\text{max}} \quad \text{and} \quad 2\sigma_j < -z_j^{\text{min}}, \ j = 1...n_z
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Market Responsive Control

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\min_{L, \Sigma_x \geq 0, \zeta_j, \sigma_j, \alpha_1, \alpha_2} \left\{ \alpha_1 \Sigma_{Ce} + \overline{C}_{e} \overline{P}_c \right\}
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\[2\sigma_j < z_j^{\max} \quad \text{and} \quad 2\sigma_j < -z_j^{\min}, \ j = 1...n_z\]

Convex Optimization Problem
Market Responsive Control

**0.0 kWhr**

![Graph showing heat flow with 0.0 kWhr](image)

**1500 kWhr**

![Graph showing heat flow with 1500 kWhr](image)

**5000 kWhr**

![Graph showing heat flow with 5000 kWhr](image)
Market Responsive Control

Instantaneous Expenditure

<table>
<thead>
<tr>
<th>Time (days)</th>
<th>Expenditure ($/hr)</th>
</tr>
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<tbody>
<tr>
<td>23</td>
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<td>9</td>
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<td>12</td>
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\[ E_{s,\text{max}} = 0 \]

\[ E_{s,\text{max}} = 1500 \]

\[ E_{s,\text{max}} = 5000 \]
## MRC Results

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<tr>
<th>$\Sigma_{Ce}$ ($$/\text{MWhr})^2$</th>
<th>$E_{\text{max}}$ (MWhr)</th>
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<td>0.0</td>
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Market Responsive Control

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\min_{L, \sum_x \geq 0, \zeta_j, \sigma_j, \alpha_1, \alpha_2} \left\{ \alpha_1 \sum_{Ce} + \overline{C_e P_c} \right\}
\]

\[\text{s.t.}\]
\[0 = (A + BL)\sum_x + \sum_x (A + BL)^T + GS_w G^T\]
\[G = G_0 + \alpha_1 G_1 + \alpha_2 G_2\]
\[\zeta_j = \rho_j (D_x + D_u L)\sum_x (D_x + D_u L)^T \rho_j^T\]
\[\sigma_j = \sqrt{\zeta_j}\]
\[2\sigma_j < z_j^{\max} \quad \text{and} \quad 2\sigma_j < -z_j^{\min}, \ j = 1...n_z\]
\[z_2^{\min} = -E_s^{\max} / 2 \quad \quad z_3^{\min} = -\overline{P_c}\]
\[z_2^{\max} = E_s^{\max} / 2 \quad \quad z_3^{\max} = P_c^{\max} - \overline{P_c}\]
\[
\min_{L, \Sigma, \zeta, \sigma, \alpha_1, \alpha_2, P_c^{\text{max}}, E_s^{\text{max}}} \left\{ c_\alpha \alpha_1 + c_c P_c^{\text{max}} + c_s E_s^{\text{max}} \right\}
\]

s.t.
\[
0 = (A + BL)\Sigma + \Sigma (A + BL)^T + GS_w G^T
\]
\[
G = G_0 + \alpha_1 G_1 + \alpha_2 G_2
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z_2^{\text{min}} = -E_s^{\text{max}} / 2 \quad \quad \quad \quad z_3^{\text{min}} = -\overline{P}_c
\]
\[
z_2^{\text{max}} = E_s^{\text{max}} / 2 \quad \quad \quad \quad z_3^{\text{max}} = P_c^{\text{max}} - \overline{P}_c
\]
\[
c_\alpha = PV_f \Sigma Ce
\]
Non-Convex  
But easily solved with branch and bound

\[
\begin{aligned}
\min_{L, \Sigma_x \geq 0, \zeta_j, \sigma_j, \alpha_1, \alpha_2, P_{c}^{\text{max}}, E_s^{\text{max}}} & \left\{ c_{\alpha} \alpha_1 + c_c P_c^{\text{max}} + c_s E_s^{\text{max}} \right\} \\
\text{s.t.} & \\
0 &= (A + BL)\Sigma_x + \Sigma_x (A + BL)^T + GS_w G^T \\
G &= G_0 + \alpha_1 G_1 + \alpha_2 G_2 \\
\zeta_j &= \rho_j (D_x + D_u L)\Sigma_x (D_x + D_u L)^T \rho_j \\
\sigma_j &= \sqrt{\zeta_j} \\
2\sigma_j &< z_j^{\text{max}} \quad \text{and} \quad 2\sigma_j < -z_j^{\text{min}}, j = 1...n_z \\
z_2^{\text{min}} &= -E_s^{\text{max}} / 2 \\
z_3^{\text{min}} &= -\bar{P}_{c} \\
z_2^{\text{max}} &= E_s^{\text{max}} / 2 \\
z_3^{\text{max}} &= P_{c}^{\text{max}} - \bar{P}_{c}
\end{aligned}
\]

\[c_{\alpha} = PV_f \Sigma Ce\]
Case Study

Equipment costs:

- 500 $/kW\text{e} for the chiller
- 28.4 $/kW_{T\text{hr}} for the TES

Present value parameters:

\[ r_i = 7\% \]
\[ n = 30\text{yrs} \]

Required chiller size without TES:

\[ P_c^{\text{max}} = 111\text{kW}_e \]
## Chiller Sizing with no cost TES

<table>
<thead>
<tr>
<th>$\Sigma_{ce}$ ($/\text{MWhr})^2$</th>
<th>$E_{s,\text{max}}$ (MW\textsubscript{Thr})</th>
<th>$P_{c,\text{max}}$ (kW\textsubscript{e})</th>
</tr>
</thead>
<tbody>
<tr>
<td>5\textsuperscript{2}</td>
<td>0.5</td>
<td>94.5</td>
</tr>
<tr>
<td>5\textsuperscript{2}</td>
<td>1.5</td>
<td>78.0</td>
</tr>
<tr>
<td>5\textsuperscript{2}</td>
<td>2.0</td>
<td>78.0</td>
</tr>
<tr>
<td>20\textsuperscript{2}</td>
<td>0.5</td>
<td>97.9</td>
</tr>
<tr>
<td>20\textsuperscript{2}</td>
<td>1.5</td>
<td>105.5</td>
</tr>
<tr>
<td>20\textsuperscript{2}</td>
<td>2.0</td>
<td>127.3</td>
</tr>
<tr>
<td>45\textsuperscript{2}</td>
<td>0.5</td>
<td>108.6</td>
</tr>
<tr>
<td>45\textsuperscript{2}</td>
<td>1.5</td>
<td>124.2</td>
</tr>
<tr>
<td>45\textsuperscript{2}</td>
<td>2.0</td>
<td>141.8</td>
</tr>
</tbody>
</table>
Chiller Sizing with no cost TES

$\Sigma C_e = (\$5/MW \text{ hr})^2$

$\Sigma C_e = (\$20/MW \text{ hr})^2$

$\Sigma C_e = (\$45/MW \text{ hr})^2$

$E_s^{\text{max}} = 1.5 \text{ MW hr}$
### Chiller and TES Sizing

<table>
<thead>
<tr>
<th>$\Sigma_{ce} \ ($/MWhr$)^2$</th>
<th>$E_s^{\text{max}}$ (MW$_{Thr}$)</th>
<th>$P_c^{\text{max}}$ (kW$_e$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20$^2$</td>
<td>0.05</td>
<td>113.8</td>
</tr>
<tr>
<td>45$^2$</td>
<td>1.15</td>
<td>106.5</td>
</tr>
</tbody>
</table>
Chiller and TES Sizing

<table>
<thead>
<tr>
<th>$\Sigma_{ce}$ ($/\text{MWhr})^2$</th>
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<td>1.15</td>
<td>106.5</td>
</tr>
</tbody>
</table>

$\Rightarrow$ 28.4 $$/\text{kW}_{\text{Thr}}$ for the TES is too expensive
Conclusions

• Market Responsive Control (MRC) an alternative to economic MPC

• MRC enables controller Embedded Equipment Design (MRC-EED)

• MRC-EED can be used to assess the economic viability of TES

• The cost of TES equipment is the current bottleneck

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