Model Predictive Control in connection with district heating networks

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Outline

Introduction

Control hierarchy aspects with MPC

Model Predictive Control in heating systems

Appendix
Introduction
... I am

• A PhD student at the Technical University of Denmark

... mostly working with

• Distributed Energy Resources (DERs) in Microgrid operation
Why Model Predictive Control (MPC) for District Heating Systems? I

Deferral of investments in additional infrastructure
Use installed system in a more efficient way

Sector coupling
Exploit additional degrees of freedom

→ In which situations can we benefit from using MPC approaches most?
Interleaved systems: Degrees of freedom in the control decisions

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Figure 1: Solar heat injection station example.
Control hierarchy aspects with MPC
A random process.. I
A random process.. II

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A quote:

*Sometimes, the best (control) decision is to do nothing*

(Source: Unknown Professor)

→ *Sometimes the best control decision is to do it differently*
Real-time problem splitting: Optimized real-time controls

Lightened problem

Complex problem

Time

Reference
Dynamic resource allocation given system condition I

- Computational budget

- Disturbance compensation at real-time:
  - Physical system
  - Sub-optimal controls

- MPC
- SP

- Physical system
- Optimal controls
- Sub-optimal controls

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Dynamic resource allocation given system condition I

Computational budget

Disturbance compensation at real-time:
- Physical system
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- Physical system
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Dynamic resource allocation given system condition I

Computational budget

Disturbance compensation at real-time:
- Physical system
- Sub-optimal controls

- Physical system
- Optimal controls
- Sub-optimal controls
Control hierarchy example: Lumped controls I

- Operational Planning stage
  - *(Stochastic Program)*

- Optimized controls
  - *(MPC)*

- Basic control
  - *(PI, PID, Explicit MPC)*

- Plant
  - *(Plant level PL)*

- Disturbances

- Dynamic Problem

- Problem size
Control hierarchy example: Separated treatment of Indirect Controls I

Planning stage

Stochastic Program

Direct–Control MPC

Direct Control, fast dynamics

Plant

Re–dispatch

Indirect Control

Slow dynamics

Prosumer
Model Predictive Control in heating systems
The master problem

\[ \dot{Q}^* = c_p \dot{m}^* \Delta \vartheta^* \]  

→ can be determined by the planning stage

The slave problem

Determine \( \vartheta^* \) at controlled sub–stations:

• Directly controlled units
• Indirectly controlled units

→ real–time collaborative MPC system support
A regulation example (Single actor)
A regulation example (Single actor) II

Figure 2: Single actor example.
Figure 3: Bottleneck with respect to magnitude (line losses).
Collaborative MPC particularities I
Collaborative MPC particularities II

- **System dynamics** magnitudes highly matter for the controller performance
  - A homogeneous system is easier to control using MPC
- System gains should be normalized
Figure 4: Improvement in the goal temperatures.
Figure 5: Improvement in the goal temperatures.
Figure 6: Improvement in the goal temperatures.
Classical regularized MPC

\[
\min_u J = \|Y - R\|_Q^2 + \|u\|_R^2 \\
\text{s.t.} \quad x_{t+1} = Ax_t + Bu_t + Gd_t + w_t \\
y_t = Cx_t \\
G_t u_t \leq h_t
\]
Tracking variation

\[
\min_u J = ||Y - R||_Q^2 + ||u - \bar{u}||_R^2
\]  \hspace{1cm} (3a)

s.t. \quad x_{t+1} = Ax_t + Bu_t + Gd_t + w_t \hspace{1cm} (3b)

\quad y_t = Cx_t \hspace{1cm} (3c)

\quad G_t u_t \leq h_t \hspace{1cm} (3d)
Figure 7: Topological toy model.
• Co-optimizing ‘certain’ and uncertain units as a collaborative MPC
• Tracking of trajectories determined by either planning or re-dispatch stage
  • Economically optimal
  • Risk optimal (Robust)
  • Trade-off trajectories
Thank you
Appendix
References

Objective function I

Stabilization problem $T_1$

$$J_{\infty,k} = ||\Phi_x(\hat{x}_k - x_{\infty,k}) + \Gamma_u(u_k - u_{\infty,k})||^2$$

(4)

Dynamic Programming problem $T_2$

$$J_{DO,k} = ||u_k - u^*_k - 1 + \gamma W_{\Delta u} \Delta u_k||^2$$

(5)

Portfolio constitution $T_3$

$$J_{C,k} = (1 - \gamma)\Pi_k$$

(6)
Objective function: Overview I

\[ \min_{u,k} \ J_{\infty,k} + J_{DO,k} + J_{C,k} \]  \tag{7} 

\[ \text{s.t.} \ \ G_k u_k \leq h_k \]  \tag{8}
Inferring input disturbance\(^1\)

\[
\begin{bmatrix}
\hat{x}_{k+1|k} \\
\hat{d}_{k+1|k}
\end{bmatrix} = 
\begin{bmatrix}
A & B_d \\
0 & I
\end{bmatrix}
\begin{bmatrix}
\hat{x}_{k|k-1} \\
\hat{d}_{k|k-1}
\end{bmatrix} +
\begin{bmatrix}
B \\
0
\end{bmatrix} u_k +
\begin{bmatrix}
L_1 \\
L_2
\end{bmatrix}
(y_{m,k} - C\hat{x}_{k|k-1} - C_d \hat{d}_{k|k-1}) \quad (9)
\]

\(^1\)We optimize over deviations encompassing the positive and negative domain → Only first optimal input required satisfactory, imposing these constraints for the whole sequence \(u_{k+N-1|k}\) results in numerical issues.
Solving for $g_\infty^2$ using least-squares approximation:

\[
\begin{bmatrix}
M \\
A - I & B \\
C & 0
\end{bmatrix}
\begin{bmatrix}
g_x,\infty \\
g_u,\infty
\end{bmatrix}
= \begin{bmatrix}
B_d \\
0
\end{bmatrix}
\quad (10)
\]

\[
g_\infty \approx \begin{bmatrix}
B_d \\
0
\end{bmatrix} M^{-1} \quad (11)
\]

\(^2\text{See Pannocchia and Rawlings 2003; Pannocchia and Rawlings 2001}\)
(T1) Equilibrium point I

\[
\begin{bmatrix}
x_\infty \\
u_\infty
\end{bmatrix} = g_\infty \hat{d}
\] (12)
Ensure offset-free control

→ Even when constraints are active on parts of the portfolio
\[
\Pi_k = \alpha \| u_k - u_{EMS,k} \|_{W_{\Delta u}}^2 + \\
\beta( \| \tilde{c}_k u_k \|^2 + \| \tilde{c}_{\Delta,k}(u_k - u_{EMS,k}) \|^2_{W_{\Delta u}} ) 
\]

where: \( \alpha + \beta = 1 \)
General
Dynamic reformulation via supervisory system: considering additional system knowledge

\[ G_k u_k \leq h_k \] (14)

Particularity: Ramp rate
Only the first optimal input in the sequence required binding

\[ \Delta u_{\text{min}} \leq u_{k+1|k}^* - u_{k|k}^* \leq \Delta u_{\text{max}} \] (15)