Optimal Design of Smart Grid Coordinated Systems

Donald J. Chmielewski

Department of Chemical and Biological Engineering
Illinois Institute of Technology
Chicago
IIT and Chicago
Presentation Outline

- Review of Economic Model Predictive Control (EMPC)
- Challenges Associated with the Design of Smart Grid Systems
- ELOC and Constrained ELOC
- Computationally Efficient Design of Smart Grid Systems
Acknowledgements

• Former Students:
  Benjamin Omell (PhD, 2013)
  David Mendoza-Serrano (PhD, 2013)
  Ming-Wei Yang (PhD, 2010)
  Jui-Kun Peng (PhD, 2004)
  Amit Manthanwar (MS, 2003)

• Current Students:
  Oluwasanmi Adeodu
  Jin Zhang

• Funding:
  National Science Foundation (CBET – 0967906)
  Wanger Institute for Sustainable Engineering Research (IIT)
Review of MPC

At time the current time, $i$, solve:

$$\min_{s_{k|i}, m_{k|i}} \left\{ \sum_{k=i}^{i+N-1} l(s_{k|i}, m_{k|i}, p_{k|i}) + l_f (s_{i+N|i}) \right\} \quad \text{s.t.}$$

$$s_{k+1|i} = f(s_{k|i}, m_{k|i}, p_{k|i})$$

$$q_{k|i} = h(s_{k|i}, m_{k|i}, p_{k|i})$$

$$q_{\min} \leq q_{k|i} \leq q_{\max} \quad k = i \ldots i + N - 1$$

$$s_{i|i} = s_i$$

Then, the manipulated variable is set as: $m_i = m_{i|i}^*$
Traditional vs. Economic MPC

In traditional MPC the objective is regulation:

\[
\min_{x_k, u_k} \left\{ \sum_{k=i}^{i+N-1} (x_{k|i}^T Q x_{k|i} + u_{k|i}^T R u_{k|i}) + x_{i+N|i}^T P x_{i+N|i} \right\}
\]

In EMPC the objective is maximize average profit (integral of instantaneous profit):

\[
\max_{s_k, m_k} \left\{ \sum_{k=i}^{i+N-1} g^{(IP)} (s_{k|i}, m_{k|i}, p_{k|i}) \right\}
\]
Economic MPC Literature

- **Conceptual Development and Stability Issues**: Rawlings and Amrit (2009); Diehl, et al. (2011); Huang and Biegler (2011); Heidarinejad, et al. (2012)

- **Process Scheduling**: Karwana and Keblisch (2007); Baumrucker and Biegler (2010); Lima et al. (2011); Kostina et al. (2011)

- **Building HVAC Systems**: Braun (1992); Morris et al. (1994); Kintner-Meyer and Emery (1995); Henze et al. (2003); Braun (2007); Oldewurtel et al. (2010), Ma et al. (2012); Mendoza and Chmielewski (2012)

- **Power Scheduling**: Zavala et al. (2009); Xie and Ilić (2009), Hovgaard, et al. (2011), Omell and Chmielewski (2013)
Economic MPC Example

A non-isothermal CSTR:

\[
\frac{dC_A}{dt} = \frac{\nu}{V} (C_{A0} - C_A) - k_0 e^{(-E/RT)} C_A
\]

\[
\frac{dC_B}{dt} = -\frac{\nu}{V} C_B + k_0 e^{(-E/RT)} C_A
\]

\[
\frac{dT}{dt} = \frac{\nu}{V} (T_0 - T) + \left( \frac{\Delta H_r}{\rho C_p} \right) k_0 e^{(-E/RT)} C_A
\]

\( T \leq 390K \)

Disturbance: \( C_{A0} = C_{A0}^{ss} \pm 0.15 C_{A0}^{ss} \)

Manipulation: \( T_0 \leq 385K \)

Instantaneous Profit:

\( g^{(IP)}(C_B) = 10 \nu C_B \)
Economic MPC Example

\[
\max_{s_{k|i}, T_{0,k|i}} \left\{ \sum_{k=i}^{i+N-1} 10 \nu C_{B,k|i} \right\} \quad \text{s.t.} \\
\begin{align*}
\ s_{k+1|i} &= f(s_{k|i}, T_{0,k|i}, C_{A0,k|i}) \\
\ s_{k|i} &= \begin{bmatrix} C_{A,k|i} & C_{B,k|i} & T_{k|i} \end{bmatrix}^T \\
\ T_{k|i} &\leq 390K \\
\ T_{0,k|i} &\leq 385K \\
\ s_{i|i} &= s_i \\
\ N &= 8
\end{align*}
\]

*Model converted to discrete-time using Euler’s explicit method.*
Economic MPC Simulation

- $C_{A0}$ (kmole/m$^3$)
- $T_0$ (K)
- $T$ (K)

Graphs showing the concentration $C_{A0}$, temperature $T_0$ and temperature $T$ over time in minutes.
Economic MPC Example

A non-isothermal CSTR:

\[ C_{A_0}, T_0, \nu \]

\[ C_A, C_B, T \]
Economic MPC Example

A non-isothermal CSTR with preheater:

\[ T_f = 303K \]

Manipulation: \( 303K \leq T_0 \leq 385K \)

Instantaneous Profit:

\[ g^{(IP)}(C_B, T_0) = \nu \left[10 C_B - 0.005 (T_0 - 303)\right] \approx \nu [5 - 0.4] \]
Economic MPC Simulation

- $C_{\text{A0}}$ (kmole/m$^3$)
- $T_0$ (K)
- $T$ (K)
Economic MPC Simulation

\[ g^{(IP)}(C_B, T_0) = v\left[10C_B - 0.005(T_0 - 303)\right] \]
Economic MPC Simulation

Change horizon from $N = 8$ to $N = 10$
Stability of EMPC

1) If $N=8$ and objective $\nu[10C_B]$, then STABLE

2) If $N=8$ and objective $\nu[10C_B - 0.005(T_0 - 303)]$, then UNSTABLE

3) If $N=10$ and objective $\nu[10C_B - 0.005(T_0 - 303)]$, then STABLE

4) If $N=10$ and objective $\nu[10C_B - 0.025(T_0 - 303)]$, then UNSTABLE

5) If $N=25$ and objective $\nu[10C_B - 0.025(T_0 - 303)]$, then STABLE
Why the Instability?

$T_f = 303K$

$$\nu \left[ 10C_B - 0.025(T_0 - 303) \right]$$

Answer: Myopic Behavior

- EMPC tries to lower costs by lowering $T_o$
- In the short run $T$, $C_B$ and Profit will remain high
- In the long run $T$, $C_B$ and Profit will drop-off
- If $N$ is small, then EMPC will not know about the drop-off
- Short term gains lead to long term losses
Presentation Outline

• Review of EMPC

• Challenges Associated with the Design of Smart Grid Systems

• ELOC and Constrained ELOC

• Computationally Efficient Design of Smart Grid Systems
Smart Grid Opportunities

Generators with Dispatch → Transmission → Consumer Demand

Renewable Sources
Energy Storage
Smart Homes
Commercial Buildings
Smart Manufacturing
Motivation for Smart Grid Coordination

Design systems to exploit these time-varying electricity prices.

Applications range from:
- Building HVAC,
- Electric Vehicle Charging,
- Distributed Generation and Storage,
- Industrial Demand Response
Building HVAC Example

Heat from Environment → Building → Chiller → Power Consumption

Houston, TX (July, 2012)

Solid – Outside Temperature

Dotted – Electricity Price
Building HVAC Example

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

Heat to TES → Thermal Energy Storage

Graph:
- Heat Flow (KW_e)
- Time (days)
- Chiller Cooling Load (Qc)

Legend:
- Heat to Chiller
- Heat from Room

Illinois Institute of Technology
Department of Chemical and Biological Engineering
HVAC Equipment Sizing Problem

Heat from Environment → Building → Heat from Building → Heat to Chiller → Chiller → Heat to TES → Thermal Energy Storage

Heat from Environment → Building → Heat from Building → Heat to Chiller → Chiller → Heat to TES → Thermal Energy Storage

Heat Flow (KW) vs Time (days)

- Blue line: Heat to Chiller
- Green dashed line: Heat from Room

2000 4000 6000

Time (days)

23 24 25 26

Heat Flow (KWe)
5 State Building Example

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

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

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

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

\[ \dot{E}_s = Q_s \]
EMPC Simulation

Solid – EMPC with TES
Dotted – EMPC without TES
EMPC Simulation with Smaller Storage

- Solid – EMPC with TES
- Dotted – EMPC without TES
Smart Grid Equipment Design Problem

Design problem is a Stochastic Program

\[
\min \left\{ PV_f \cdot OpCost + CapCost \right\}
\]

\[
OpCost \approx \min_{0 \leq OpVar_k \leq EquipSize} \left\{ \frac{1}{N} \sum_{k=1}^{N} \text{InstOpCost}(OpVar_k) \right\}
\]

If no energy storage, then two-stage problem
If energy storage is allow, then a multistage problem
Possible Solution Method

Gradient Search

\[
\text{minimize } PV
\]

Provide: Equipment Sizes

Return: Average Expenditure

EMPC Simulations
Inventory Creep

Simulation Period: 28 days
Operating Cost (no TES): $759
Operating Cost Reduction with 1.5MWhr: 31.4%
Simulation Time: 1.4 hrs
EMPC Horizon Size: 24 hrs

Operating Cost Reduction with 1.5MWhr: 13.8%
Simulation Time: 6.7 sec
EMPC Horizon Size: 3 hr

Solid – EMPC with 24hr horizon
Dotted – EMPC with 3hr horizon
Use of Surrogate Controllers

Gradient Search
minimize $PV$

Provide: Equipment Sizes

Return: Average Expenditure

EMPC Simulations

ELOC

Constrained ELOC
Presentation Outline

- Review of EMPC
- Challenges Associated with the Design of Smart Grid Systems
- ELOC and Constrained ELOC
- Computationally Efficient Design of Smart Grid Systems
Economic Linear Optimal Control (ELOC)

\[ u_i = L_{ELOC} x_i \]

Steady-State Operating Line

Expected Dynamic Operating Regions

Minimally Baked-off Operating Point

Different Controller Tuning Values

Optimal Steady-State Operating Point
Economic Linear Optimal Control

\[
\min \left\{ g_{op,\text{cost}}(q, \Sigma_z) \right\}
\]

\[
s.t. \quad s = f(s, \overline{m}, \underline{p}, \Sigma_z) \quad q = h(s, \overline{m}, \Sigma_z)
\]
\[
\Sigma_x = (A + BL) \Sigma_x (A + BL)^T + G \Sigma_w G^T
\]
\[
\Sigma_z = (D_x + D_u L) \Sigma_x (D_x + D_u L)^T
\]
\[
\sigma_{z,j} \leq q_j^{\max} - q_j \quad \sigma_{z,j} \leq q_j - q_j^{\min}
\]

Global Solutions can be efficiently determined using GBD
CSTR Example

Statistical constraints are clearly enforced.
What about point-wise-in-time constraints?

→ Constrained ELOC
Linear Quadratic Regulator

\[
\min_{x_{k|i}, u_{k|i}} \left\{ \sum_{k=i}^{i+N-1} (x_{k|i}^T Q x_{k|i} + u_{k|i}^T R u_{k|i}) + x_{i+N|i}^T P x_{i+N|i} \right\} \quad \text{s.t.}
\]

\[
x_{k+1|i} = A x_{k|i} + B u_{k|i}
\]

\[
x_{i|i} = x_i
\]

\[
u_i = L_{LQR} x_i
\]

Predictive Form of ELOC

\[
\min_{x_{k|i}, u_{k|i}} \left\{ \sum_{k=i}^{i+N-1} (x_{k|i}^T Q_{ELOC} x_{k|i} + u_{k|i}^T R_{ELOC} u_{k|i}) + x_{i+N|i}^T P_{ELOC} x_{i+N|i} \right\} \quad \text{s.t.}
\]

\[
x_{k+1|i} = A x_{k|i} + B u_{k|i}
\]

\[
x_{i|i} = x_i
\]

\[
u_i = L_{ELOC} x_i
\]

* see Chmielewski & Manthanwar (2004) for details
Constrained ELOC

\[
\min \left\{ \sum_{k=i}^{i+N-1} \left( x_{k|i}^T Q_{ELOC} x_{k|i} + u_{k|i}^T R_{ELOC} u_{k|i} \right) + x_{i+N|i}^T P_{ELOC} x_{i+N|i} \right\} \quad \text{s.t.}
\]

\[
x_{k+1|i} = Ax_{k|i} + Bu_{k|i}
\]

\[
x_{i|i} = x_i
\]

\[
z_{k|i} = Dx_{k|i} + Du_{k|i}
\]

\[
z^\text{min} \leq z_{k|i} \leq z^\text{max}
\]
Constrained ELOC

![Graphs showing temperature T(K) vs. manipulated variable T0(K) and reactor temperature T(K) vs. manipulated variable Tin(K).]
Constrained ELOC
Constrained ELOC and Horizon Size

![Graph showing temperature changes with EMPC and constrained ELOC N=1 and N=10](image-url)

- Black line: EMPC
- Red line: Constrained ELOC N=1
- Green dashed line: Constrained ELOC N=10
Constrained ELOC and Nonlinear Plants

\[
\min_{x_{k|i}, u_{k|i}} \left\{ \sum_{k=i}^{i+N-1} (x_{k|i}^T Q_{ELOC} x_{k|i} + u_{k|i}^T R_{ELOC} u_{k|i}) + x_{i+N|i}^T P_{ELOC} x_{i+N|i} \right\} \quad \text{s.t.}
\]

\[
x_{k+1|i} = f(x_{k|i}, u_{k|i}) \quad x_{i|i} = x_{i}
\]

\[
z_{k|i} = h(x_{k|i}, u_{k|i})
\]

\[
z_{\min} \leq z_{k|i} \leq z_{\max}
\]
ELOC in Building HVAC

Figure 4.3. PSI ELOC (solid) and EMPC (dashed) policies for a ZFI 4th order forecasting model with historic data.
Figure 5.1. PSI Constrained ELOC (solid) and EMPC (dashed) policies for a ZFI 4th order forecasting model.
Horizon Size Insensitivity

Figure 5.2. PSI Constrained ELOC policy for $N = 2$ (dashed) hrs and $N = 24$ (solid) hrs a ZFI $4^{th}$ order forecasting model.
Computational Efficiency

Table 5.1. Computational effort comparison for EMPC ZFI and Constrained ELOC ZFI with 1.5 \( MW_{Thr} \) storage capacity for 28 days simulation.

<table>
<thead>
<tr>
<th></th>
<th>Computational Effort (secs)</th>
<th>Percent Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMPC with ( N = 24 ) hrs</td>
<td>13,321</td>
<td>—</td>
</tr>
<tr>
<td>EMPC with ( N = 2 ) hrs</td>
<td>6.05</td>
<td>99.95%</td>
</tr>
<tr>
<td>PSI Constrained ELOC with ( N = 2 ) hrs</td>
<td>2.61</td>
<td>99.98%</td>
</tr>
<tr>
<td>FSI Constrained ELOC with ( N = 2 ) hrs</td>
<td>4</td>
<td>99.97%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Expenditure</th>
<th>Percent Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMPC FFI with No TES</td>
<td>$759</td>
<td>—</td>
</tr>
<tr>
<td>EMPC FFI with TES</td>
<td>$521</td>
<td>31.4%</td>
</tr>
<tr>
<td>EMPC ZFI with ( N = 24 ) hrs</td>
<td>$556</td>
<td>26.7%</td>
</tr>
<tr>
<td>EMPC ZFI with ( N = 2 ) hrs</td>
<td>$674</td>
<td>11.2%</td>
</tr>
<tr>
<td>FSI Constrained ELOC with ( N = 2 ) hrs</td>
<td>$562</td>
<td>26.0%</td>
</tr>
<tr>
<td>PSI Constrained ELOC with ( N = 2 ) hrs</td>
<td>$526</td>
<td>30.7%</td>
</tr>
</tbody>
</table>
Presentation Outline

- Review of EMPC
- Challenges Associated with the Design of Smart Grid Systems
- ELOC and Constrained ELOC
- Computationally Efficient Design of Smart Grid Systems
Where Are We?

- **EMPC**
  - Provides economically optimized performance
  - Need for large horizons makes it slow

- **ELOC and Constrained ELOC**
  - Both are good surrogates for EMPC
  - Both are computationally fast

- **Objective**: Use ELOC to enable computational tractability of Equipment Design problem
Use of Surrogate Controllers

Gradient Search
minimize $PV$

Provide:
Equipment Sizes

Return:
Average Expenditure

EMPC Simulations

ELOC

Constrained ELOC
Possible Search Scheme

Global Search with ELOC

minimize NPV
over here-and-now variables and ELOC parameters

Statistical Constraint Enforcement
ELOC Based Design

\[
\min_{\bar{s}, \bar{m}, \bar{q}, L, \Sigma_x, \Sigma_z, q_j^{\text{max}}, q_j^{\text{min}}} \left\{ g_{\text{op.cost}}(\bar{q}, \Sigma_z) + g_{\text{cap.cost}}(q_j^{\text{max}}, q_j^{\text{min}}) \right\}
\]

\[
s.t. \quad \bar{s} = f(\bar{s}, \bar{m}, \bar{p}, \Sigma_z) \quad \bar{q} = h(\bar{s}, \bar{m}, \Sigma_z)
\]

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

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

\[
\sigma_{z,j} \leq q_j^{\text{max}} - \bar{q}_j \quad \sigma_{z,j} \leq \bar{q}_j - q_j^{\text{min}}
\]

Global Solutions can be determined efficiently using GBD
HVAC Equipment Sizing Problem

Heat from Environment

Building

Heat from Building

Heat to Chiller

Chiller

Power Consumption

Heat to TES

Thermal Energy Storage
ELOC Based Design

\[ c_c = 500 \$/kW_e \]

Figure 6.3. ELOC policy for \( c_s = 28.4 \$/kW_T/hr \).

Figure 6.4. ELOC policy for \( c_s = 14.2 \$/kW_T/hr \).

Figure 6.5. ELOC policy for \( c_s = 2.8 \$/kW_T/hr \).
Proposed Search Scheme

Global Search with ELOC

- minimize NPV
- over here-and-now variables and ELOC parameters
- Statistical Constraint Enforcement

Gradient Search with Constrained ELOC

Constrained ELOC Simulations
- Point-wise-in-time Constraint Enforcement

Provide:
- here-and-now values

Gradient Search
- minimize NPV
- over here-and-now variables

Return:
- minimum average operating costs
Gradient Search with Constrained ELOC

$c_s = 14.2 \$/kW_T/hr$ and $c_c = 500 \$/kW_e$
Constrained ELOC with Soft Constraints

\[
\min_{x_{k|i}, u_{k|i}} \left\{ \sum_{k=i}^{i+N-1} (x_{k|i}^T Q_{ELOC} x_{k|i} + u_{k|i}^T R_{ELOC} u_{k|i}) + x_{i+N|i}^T P_{ELOC} x_{i+N|i} + c_s s \right\}
\]

s.t.

\[
x_{k+1|i} = A x_{k|i} + B u_{k|i}
\]

\[
x_{i|i} = x_i
\]

\[
z_{k|i} = D_x x_{k|i} + D_u u_{k|i}
\]

\[
z_{\min} - s \leq z_{k|i} \leq z_{\max} + s
\]
Penalty for Infeasible Operation

![Graph showing present value vs. P_c^{max} (kW_e)]

Table 6.2. Equipment sizing gradient search trajectory

<table>
<thead>
<tr>
<th>Penalty</th>
<th>E_s^{min} (kW_T/hr)</th>
<th>P_c^{max} (kW_T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>-604.7</td>
<td>38.7</td>
</tr>
<tr>
<td>1</td>
<td>-845.0</td>
<td>25.6</td>
</tr>
<tr>
<td>10</td>
<td>-1105.1</td>
<td>48.9</td>
</tr>
<tr>
<td>100</td>
<td>-1295.9</td>
<td>46.8</td>
</tr>
<tr>
<td>1e3</td>
<td>-1098.5</td>
<td>49.9</td>
</tr>
<tr>
<td>1e4</td>
<td>-1098.5</td>
<td>49.9</td>
</tr>
</tbody>
</table>
Conclusions

- **EMPC**
  - Provides economically optimized performance
  - Need for large horizons makes it slow

- **ELOC and Constrained ELOC**
  - Both are good surrogates for EMPC
  - Both are computationally fast

- **Equipment Design for Smart Grid Systems**
  - ELOC enables computational tractability
  - Penalty method developed to address infeasibilities
Design of Dispatchable Energy Storage

\[ 0 \leq E_{S1} \leq E_{S1}^{\text{max}} \]

\[ 0 \leq E_{S2} \leq E_{S2}^{\text{max}} \]

\[ \text{CapCost}_j = 100,000 \times E_{S_j}^{\text{max}} \]

ELOC Solution:

\[ E_{S1}^{\text{max}} = E_{S2}^{\text{max}} = 239 \text{ MWhr} \]
ELOC Operating Region with ELOC Optimal Storage Sizing