A Plantwide Control Procedure with Application to Control Structure Design for a Gas Power Plant

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Outline

- Gas power plant
- Plantwide control
- Plantwide control procedure
- Application
- Concluding remarks
Gas power plant

- Fuel compressor
- Air compressor
- Combustor
- Gas turbine
- Pre-heater
- Super-heater
- Evaporator
- Economizer
- Steam-turbine
- Condenser
- LP-pump
- Deaerator
- HP-pump
- Condenser drum
- z=0
- z=1
Plantwide Control

*Structural decisions of the control system for an overall plant*

Important questions:
1. Which variable to control
2. Which variable to manipulate
3. Which control configuration
4. Which controller type

Difficult:
Integrated processes
Plantwide Control Procedure
(Larsson and Skogestad, 2000)

I. Top down analysis
   1. Manipulated variables
   2. Degree of freedom analysis
   3. Primary controlled variables (steady-state economics)
   4. Production rate manipulator

II. Bottom up design of the control system
   5. Structure of regulatory control layer
      (secondary control variables)
   6. Structure of supervisory control layer (MPC applications)
   7. Structure of optimization layer
Step 1. Manipulated variables: 13
Step 2. Steady-state degrees of freedom: 8

DOF: 13-2(levels without steady-state effect)-1(deaerator pressure)-2(turbine speeds)=8
Step 3. Primary controlled variables

3.1 Degrees of freedom for optimization
3.2 Define optimal operation (cost and constraints)
3.3 Identification of important disturbances
3.4 Optimization
3.5 Identification of candidate controlled variables
3.6 Evaluation of loss
3.1 Degrees of freedom for optimization: 8

3.2 Define optimal operation
Maximize profit:

\[-J = 0.1W_{net} - F_{fuel}\]

Constraints:
\[
\begin{align*}
T_{\text{combustor}} & \leq 1500 \text{ C} & \text{active} \\
T_{g,\text{super,in}} & \leq 550 \text{ C} \\
T_{w,\text{pre,in}} & \geq 63 \text{ C} \\
F_{LPvalve} & \leq F_{LPvalve,\text{max}} & \text{active} \\
F_{cw} & \leq F_{cw,\text{max}} & \text{active} \\
Flows & \geq 0 & 4 \text{ active}
\end{align*}
\]

3.3 Disturbances: \( d = T_{\text{air}} = 20 \pm 10^\circ C \)

3.4 Optimization: 7 optimal active constraints
**Step 3.5: Identify candidate controlled variables**

Use active constraint control $\Rightarrow 8-7=1$ unconstrained variable

<table>
<thead>
<tr>
<th>Candidates</th>
<th>Implementation error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flowrates</td>
<td>$\pm 10%$</td>
</tr>
<tr>
<td>Pressures</td>
<td>$\pm 2.5%$</td>
</tr>
<tr>
<td>Temperatures</td>
<td>$\pm 1^\circ C$</td>
</tr>
<tr>
<td>Flowratios</td>
<td>$\pm 20%$</td>
</tr>
<tr>
<td>Work</td>
<td>$\pm 30%$</td>
</tr>
<tr>
<td>Duty</td>
<td>$\pm 30%$</td>
</tr>
<tr>
<td>Compressor speed</td>
<td>10%</td>
</tr>
<tr>
<td>Combustor temperature</td>
<td>$\pm 10^\circ C$</td>
</tr>
</tbody>
</table>

Which variable should be controlled?
Screening of candidate controlled variables

Maximize steady-state gain (|G(0)|)

| Rank | $c_8$             | $|G(0)|$   |
|------|-------------------|-----------|
| 1    | $T_{g,super,in}$  | 7.6936    |
| 2    | $P_{combustor}$   | 3.6352    |
| 3    | $F_{air}$         | 2.3358    |
| 4    | $F_{fuel}$        | 0.9587    |
| 5    | $F_{fuel}/F_{air}$| 0.6211    |
| 6    | $T_{w,pre,in}$    | 0.1102    |
## Step 3.6 Loss evaluation with nominal setpoints

<table>
<thead>
<tr>
<th>Rank</th>
<th>Alt./$c_{s,8}$</th>
<th>Average loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>On-line opt.</td>
<td>2.40%</td>
</tr>
<tr>
<td>1</td>
<td>$T_g,\text{super, in}$</td>
<td>2.56%</td>
</tr>
<tr>
<td>2</td>
<td>$P_{\text{combustor}}$</td>
<td>2.60%</td>
</tr>
<tr>
<td>3</td>
<td>$F_{\text{air}}$</td>
<td>3.21%</td>
</tr>
<tr>
<td>-</td>
<td>$F_{\text{fuel}}$</td>
<td>Infeasible</td>
</tr>
<tr>
<td>-</td>
<td>$F_{\text{fuel}}/F_{\text{air}}$</td>
<td>Infeasible</td>
</tr>
<tr>
<td>-</td>
<td>$T_{w,\text{pre, in}}$</td>
<td>Infeasible</td>
</tr>
</tbody>
</table>

*Cost $J$*

*Disturbance $d$*

*Reoptimized $J_{\text{opt}}(d)$*

*C$_{2,s}$ = constant*

*C$_{1,s}$ = constant*

*Loss*
Step 4. Production rate manipulator

Not relevant for gas phase system
So far:

Self-optimizing variable
(unconstrained)
II: Bottom-up design of control system
Step 5. Structure of regulatory control layer

Stabilization:
Evaporator drum level ↔ LP-pump flowrate
Condenser drum level ↔ HP-pump flowrate

Local disturbance rejection: Use local flow controller
Step 6. Structure of supervisory control layer
Proposed decentralized control structure

\[
RGA(0) = \begin{bmatrix}
1.87 & -0.87 & 0 \\
-0.87 & 1.87 & 0 \\
0 & 0 & 1
\end{bmatrix}
\]
Step 7. Structure of optimization layer

On-line optimization is not needed.

Loss:
Super-heater inlet temperature : 2.56%
On-line optimization : 2.40%
Validation by simulation: $\Delta T_{air} = +10^\circ C$
Concluding remarks

- Demonstrated a systematic procedure for selection of plantwide control structure on a simple gas power plant.

- Control: Super-heater gas inlet temperature
  ⇒ simple system + close to optimal operation
Step 3.6 Optimal back-off by robust optimization off-line (Glemmestad et al., 1998)

Robust optimization:

\[
\min_{x_i, u_i, c_s} \sum_i w_i J(x_i, u_i, d_i)
\]

\[
f(x_i, u_i, d_i) = 0
\]

\[
g(x_i, u_i, d_i) \leq 0
\]

\[
c(x_i, u_i, d_i) \equiv c_s + n_i
\]

\[
d_i \in D
\]

\[
e_i \in E
\]

"Optimal back-off":

\[
b_{opt} = c_{s,\text{robust}} - c_{s,\text{opt}}(d_0)
\]

\[
F_{fuel}: \text{Loss} = 9.44\%, \quad b_8 = -2.60
\]
Step 3.6 Flexible back-off from nominal setpoints online (Lid et.al., 2001)

\[ \min_{x, u, c_{s, flex}} (c_s - c_{s, flex}) Q(c_s - c_{s, flex}) \]

\[ f(x, u, d) = 0 \]
\[ g(x, u, d) \leq 0 \]
\[ c(x, u, d) = c_{s, flex} + n \]
\[ c_s = c_{s, opt}(d_0) \]
\[ d \in D \]
\[ e \in E \]

“Flexible back-off”:
\[ b_{flex} = c_{s, flex}(d) - c_{s, opt}(d_0) \]

\[ F_{fuel}: \text{Loss}=9.23\%, \ b_8=[-5.1, 0] \]