Performance Limitations arising in the Control of Direct Fired Coal Power Plants

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Outline

Motivation
- Context
- Direct fired coal power plants
- Main Problem

MIMO performance bounds
- Some classical results
- Multiobjective optimization
- Controller design
- Control cost
- Solution to main problem

Simulation results

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**Summary**
Electricity Market becomes more competitive

- Privatization of former state monopolies
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- Distributed market: Many producers, many sources
Electricity Market becomes more competitive

- Privatization of former state monopolies
- Distributed market: Many producers, many sources
- Biggest value for highest flexibility
Two main control modes for power units

- Primary frequency control
  - instantaneous load adaptation (within a few percents) as a function of grid frequency variation
  - direct action on turbine valves
  - security mode (e.g. if steam pressure in boiler drops too much)
Two main control modes for power units

- **Primary frequency control**
  - instantaneous load adaptation (within a few percents) as a function of grid frequency variation
  - direct action on turbine valves
  - security mode (e.g., if steam pressure in boiler drops too much)

- **Secondary frequency control**
  - frequent load setpoint adaptation as determined by grid manager
  - large load gradients can be expected
  - only combined cycle gas turbines (Electrabel)
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Summary
Classical Decentralized Control Strategies

- Boiler following mode
  - turbine inlet valves control load (fast action)
  - boiler is a steam (energy) buffer
  - fuel flow adjusted to control steam pressure (slow action)

- Turbine following mode
  - steam pressure controlled by turbine valves (fast action)
  - fuel flow controls load (slow action on load)
  - control strategy for base load (and coal fired power plants)

- Sliding pressure mode
  - fuel flow controls load
  - turbine inlet valves remain constant, hence sliding pressure
  - safety mode if pressure outside given limits

- Improved unit efficiency
Classical Decentralized Control Strategies

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Summary
Best achievable performance using MIMO controller

Can a direct fired coal power plant participate in secondary grid frequency control, despite the large delay on fuel input due to coal grinding?

Find performance limits of ANY MIMO controller when load set point is a step change and there is a bound on the norm of steam pressure deviation.
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Summary
Define the cost functional

\[ J = \sum_{k=0}^{\infty} e^T(k)e(k) \]

where \( e(k) \) denotes the tracking error of a one D.O.F. control loop, for a step reference signal, \( r(k) = v\mu(k) \).
Chen et al.
Let $G(z) = \Lambda(z) G_{nd}(z)$, where $G_{nd}(z)$ contains no delay and

$$\Lambda(z) = \begin{bmatrix} z^{-d_1} & \cdots & \cdots & z^{-d_p} \end{bmatrix}$$

Then

$$J_{opt} = \sum_{i=1}^{p} d_i v_i^2 + J_{nd}$$
Some classical results

Performance bounds for NMP MIMO systems with delays

Salgado, Silva (more general result):

\[
\tilde{G}(z) = \hat{\xi}_g U(z) G(z)
\]  

(1)

where \(\hat{\xi}_g U(z)\) is the unit. interactor with unity DC-gain for \(G(z)\). (i.e. \(\tilde{G}(z)\) is biproper).

\[
J_{opt} = \sum_{i=1}^{m} |\eta_i^H v|^2 + J_{NMP}
\]

where \(m\) is relative degree of plant,
\(\eta_i\) appears in construction of left unitary interactor matrix.
Cost is measure of deviation from perfect inversion
Comments

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- Chen result no good for us
- Unitary interactor is key
- NMP zeros have also a specific effect
- We have a more specific cost in mind
MIMO performance bounds

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Our problem: Multiobjective optimization

Consider MIMO (2 X 2) model of plant

\[ G(z) = \begin{bmatrix}
\frac{0.327z-0.3376}{z^2-1.695z+0.7011} & \frac{10^{-4}(3.897z+3.714)}{z^{20}(z^2-1.862z+0.8651)} \\
-\frac{0.007282z-0.006811}{z^2-1.814z+0.8182} & \frac{10^{-4}(3.974z+3.822)}{z^{20}(z^2-1.887z+0.8898)}
\end{bmatrix} \]

Minimize simultaneously load tracking error norm \((J)\) and steam pressure deviation norm \((R)\).

\[
J = \sum_{k=0}^{\infty} e_1(k)^2, \quad R = \sum_{k=0}^{\infty} e_2(k)^2,
\]

where \(e_i\) is the \(i\)-th component of the tracking error when the reference is given by \(r = \epsilon_1 \mu\).
Characterization of achievable specifications - Pareto optimality

Use Youla parametrization of all stabilizing controllers
Define set of achievable objectives:

\[ A = \{ (\alpha_J, \alpha_R) \in \mathbb{R}^2 : \alpha_J \geq J(Q(z)), \]
\[ \alpha_R \geq R(Q(z)), \text{ for some } Q(z) \in \mathcal{RH}_\infty \} \]

\[ L_\lambda(Q(z)) = J(Q(z)) + \lambda R(Q(z)), \]
\[ Q_\lambda(z) = \arg\min_{Q(z)\in\mathcal{RH}_\infty} L_\lambda(Q(z)). \]

The set of Pareto optimal points associated with \( A \) is given by

\[ \mathcal{P} = \{ (\alpha_J, \alpha_R) \in \mathbb{R}^2 : \alpha_J = J(Q_\lambda(z)), \]
\[ \alpha_R = R(Q_\lambda(z)), \text{ for some } \lambda \geq 0 \}. \]
Achievable performance

Region of achievable performance

achievable trade-offs

best trade-offs

R

J

0 2 4 6 8 10 12 14 16

0 2 4 6 8 10 12 14 16

0 2 4 6 8 10 12 14 16

0 2 4 6 8 10 12 14 16

Vincent Wertz, INMA ()

Control of Power Plants

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Characterization of $Q_\lambda(z)$

> If $\lambda > 0$, then

$$Q_\lambda(z)\epsilon_1 = (\xi_\Lambda(z)G_\Lambda(z))^{-1}\Lambda\epsilon_1,$$

where

$$\Lambda = \begin{pmatrix} 1 & 0 \\ 0 & \sqrt{\lambda} \end{pmatrix}, \quad G_\Lambda(z) = \Lambda G(z)$$

and $\xi_\Lambda(z)$ is a left unitary interactor for $G_\Lambda(z)$ having unit DC-gain

> similar expressions for the cases $\lambda = 0$ and $\lambda \to \infty$

> notice only first column of $Q_\lambda(z)$ is prescribed.
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Tracking error as a function of $\lambda$

Let $m$ denote the relative degree of $G(z)$, i.e., the number of zeros at infinity, and $m_{ij}$ denote the relative degree of $G_{ij}(z)$.

If $m > m_{21}$, $m_{22} > m_{21}$ and $G_{21}(z)$ is MP, then:

1. If $\lambda > 0$, then

$$J(Q_{\lambda}(z)) = \| \epsilon_1^T \frac{I - \Lambda^{-1} \xi(z)^{-1} \Lambda}{z - 1} \epsilon_1 \|_2^2$$

2. If $\lambda = 0$, then

$$J(Q_0(z)) = m_{11}$$

3. When $\lambda \to \infty$, then

$$J(Q_{\infty}(z)) = m - m_{21}$$
Tracking error as a function of $\lambda$

In our case where the plant has large relative degree (i.e., large delays) concentrated in the second column, by means of varying $\lambda$ one can attain a load tracking error norm that ranges from the relative degree of $G_{11}(z)$ (when $\lambda \to 0$) to the difference between the relative degree of the MIMO model and that of $G_{21}(z)$ (when $\lambda \to \infty$). Hence it may be possible to achieve good tracking performance by means of choosing a small $\lambda$. Of course, this comes at the expense of large error norm on the second output.
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Main result

Define

\[ J_{\text{opt}} = \min_{Q(z) \in \mathcal{RH}_\infty, R(Q(z)) \leq M} J(Q(z)), \]
\[ R_0 = \min_{X_1(z) \in \mathcal{RH}_\infty} R(Q_0(z)), \]
\[ R_\infty = R(Q_\infty(z)) \]
Main result (cont’d)

Then:

1. If $M \in (R_{\infty}, R_0)$, then the optimal Youla parameter $Q_{opt}(z)$ is given by

$$Q_{opt}(z) = (\xi_{\Lambda_o}(z)G_{\Lambda_o}(z))^{-1}\Lambda_o,$$

with $\lambda_0$ s.t. $\|\epsilon_2^T \frac{I - \Lambda_o^{-1}\xi_{\Lambda_o}(z)^{-1}\Lambda_o}{z - 1} \epsilon_1\|^2 = M$. 

2. If $M \geq R_0$, then $Q_{opt}(z) = Q_0(z)$

3. If $M = R_{\infty}$, then $Q_{opt} = Q_{\infty}(z)$

4. If $M < R_{\infty}$, then Problem 1 is infeasible.
Main result (cont’d)

Then:

1. If \( M \in (R_\infty, R_0) \), then the optimal Youla parameter \( Q_{opt}(z) \) is given by

\[
Q_{opt}(z) = (\xi \Lambda_o(z) G \Lambda_o(z))^{-1} \Lambda_o,
\]

with \( \lambda_0 \) s.t.
\[
\| \epsilon^T \left( I - \frac{\Lambda_o^{-1} \xi \Lambda_o(z)^{-1} \Lambda_o}{z-1} \right) \epsilon_1 \|_2^2 = M.
\]

2. If \( M \geq R_0 \), then \( J_{opt} = m_{11} \) and \( Q_{opt}(z) = Q_0(z) \)
Main result (cont’d)

Then:

1. If $M \in (R_\infty, R_0)$, then the optimal Youla parameter $Q_{opt}(z)$ is given by

$$Q_{opt}(z) = (\xi_{\Lambda_o}(z)G_{\Lambda_o}(z))^{-1} \Lambda_o,$$

with $\lambda_0$ s.t. $\|\epsilon_2^T \frac{I - \Lambda_o^{-1} \xi_{\Lambda_o}(z)^{-1} \Lambda_o}{z - 1} \epsilon_1\|_2^2 = M$.

2. If $M \geq R_0$, then $J_{opt} = m_{11}$ and $Q_{opt}(z) = Q_0(z)$.

3. If $M = R_\infty$, then $J_{opt} = m - m_{21}$ and $Q_{opt} = Q_\infty(z)$. 

4. If $M < R_\infty$, then Problem 1 is infeasible.
Main result (cont’d)

Then:

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with \( \lambda_0 \) s.t.

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\| \epsilon_T \frac{I - \Lambda^{-1}_o \xi \Lambda_o(z)^{-1} \Lambda_o}{z - 1} \epsilon_1 \|_2^2 = M.
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2. If \( M \geq R_0 \), then \( J_{opt} = m_{11} \) and \( Q_{opt}(z) = Q_0(z) \)

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Summary
Different cost terms as a function of $\lambda$
Simulation results

Load and vapour pressure responses

- Load response to a reference step change at $t = 10$
- Vapour pressure response to a reference step change in load at $t = 10$

$M = 4$
$M = 3$
$M = 2$
$M = 1$
$M = 0.45$
$M = 4$
$M = 3$
$M = 2$
$M = 1$
$M = 0.45$

[Graphs showing load and vapour pressure responses for different values of $M$.]
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Take Home Messages

- Theoretical "benchmark": no constraints on control effort
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- Theoretical "benchmark": no constraints on control effort
- Controller design with more constraints using other techniques (LMI, MPC)
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- Theoretical "benchmark" : no constraints on control effort
- Controller design with more constraints using other techniques (LMI, MPC)
- MIMO controller could replace multiple decentralized control strategies with complex switching logic