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Emnemodul: Advanced process control

02 Dec. 2011. Time: 0915 – 1200. Answer as carefully as possible, preferably using the available space. You may answer in Norwegian

Problem 1 (30%).

(a) Define self-optimizing control:

3/3 Near-optimal control ~~achieved by~~ with acceptable loss achieved by keeping controlled variables at a constant setpoint.

(b) How can you identify good primary controlled variable (in words)?

4/5 The first primary controlled variables are the one related to the active constraints. ✓ Good primary controlled variables are sensitive to the inputs (large gain) and insensitive [optimal value] to the disturbances. The objective function plotted as a function of them has a flat curve.

(c) What is back-off and how can it be reduced?

3/3 The back-off is the safety margin taken to not crossover a specific constraint of a controlled variable.

It can be reduced by ~~squeezing and shifting~~ "squeeze and shift", reducing the variance of the controlled variable.

(d) What can you say about the purity specification (constraint) of a "valuable" and "cheap" product? Which is expected to be active?

If the product is valuable, the purity specification is an active constraint due to the fact it is not economical to over-purify it (and doing so diminish its total flowrate).

3/3 If the product is cheap, the purity specification is not ~~anyway~~ systematically an active constraint ~~anyway~~, the product can be over-purified to diminish, for example, the energy cost of the process.

(e) Consider controlling (CV) a measurement combination, $\Delta c = H\,\Delta y$.
Explain under which conditions it is optimal to choose H such that HF=0 (nullspace method). Define F and derive the condition HF=0.

6/6 The number of measurements has to be higher or equal to than the number of inputs and disturbances. No measurement noise. ✓

$$F = \frac{\partial y_{opt}}{\partial d} \rightarrow \Delta y_{opt} = F d \;\; \forall d$$

$$\Delta C_{opt} = 0 \Leftrightarrow H \Delta y_{opt} = 0 \Leftrightarrow HFd = 0 \text{ for any } d. \Leftrightarrow HF = 0$$

(f) Consider a process with one steady-state degree of freedom (u), two disturbances (d1, d2) and three measurements (y1, y2, y3). Use the nullspace method to derive the optimal measurement combination when F = (3 1 ; 3 0.6; 0 1).

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$$HF = 0$$

$$[h_1\ h_2\ h_3]\begin{bmatrix}3 & 1\\ 3 & 0{,}6\\ 0 & 1\end{bmatrix} = [0\ \ 0]$$

$$\Leftrightarrow \begin{cases} 3h_1 + 3h_2 = 0 \\ h_1 + 0{,}6\,h_2 + h_3 = 0 \end{cases} \quad \text{fix } h_1 = 1 \Leftrightarrow \begin{cases} h_1 = 1 \\ h_2 = -1 \\ h_3 = -0{,}4 \end{cases}$$

$$C_{opt} = y_1 - y_2 - 0{,}4\,h_3$$ ✓

(g) Why may we sometimes get more then one optimal combination when we use the nullspace method (for example, for the blending example in one of the exercises) ?

3/3 $HF = 0$ leads to a unique solution only if $n_y = n_d$.
For processes where we have many measurements and a few disturbances, many combinations can be obtained. When $n_y = n_d + 1$, only linear combination can be obtained (no interest).

(h) Explain briefly the advantages of the "exact local method"

3/3 This method takes into account the measurement noise.

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Problem 2 (10%).

(a) State the steps of the plantwide control procedure of Skogestad, and give a *short* explanation of the main issues in each step.

I) Top-down

Step S1: Define objective function and constraints ✓

↳ economical evaluation of $J(u, x, d)$; $f(u,x,d) = 0$ and $g(u,x,d) \geq 0$

Step S2: Identify degrees of freedom and optimize for given disturbances ✓

↳ Equation counting / Valve counting - optimization issues

Step S3: (Implement control strategy) What to control? (primary CVs) ✓

↳ Set CVs to active constraints / use self-optimizing CVs for remaining DOFs.

Step S4: Where set the production rate? ✓

↳ Locate the throughput manipulator (TPM)

II) Bottom-up

Step S5: Regulatory control layer. What more to control? ✓

↳ Identify CVs for stabilizing the process (fast control), identify a good pairing.

Step S6: Supervisory control layer. ✓

↳ Implement Model Predictive Control or decentralized control (or sequential)

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Step S7: Real-time optimization. ✓

↳ Introduction if necessary (if we do not have self-optimizing CVs for all constraint region)

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(b) Is it correct that we like choosing constrained variables as CVs in the "supervisory" layer and avoid choosing variables that may reach constraints as CVs in the "stabilizing" layer? Explain.

Yes, it is correct. We have to avoid saturation of the inputs in the stabilizing layer.

↑ not asked for ...

Problem 3 (RGA and pairing). **(15%)**

You want to control 2 outputs (CVs) and have available 3 inputs.

$y_1 = [0.9/(5s+1)]\,u_1 + [0.8/(5s+1)(3s+1)]\,u_2 + [-1/(5s+1)]\,u_3$
$y_2 = [0.4\,e^{-2s}/(5s+1)]\,u_1 + [0.3/(5s+1)(3s+1)]\,u_2 + [-0.2/(5s+1)]\,u_3$

The task is to make a simple control structure with two single loops (using only 2 of the inputs).

(a) Compute the steady-state RGA for the three alternative input combinations.

1) u_1 & u_2:

$G_{s-s_1} = \begin{bmatrix} 0{,}9 & 0{,}8 \\ 0{,}4 & 0{,}3 \end{bmatrix} \Rightarrow RGA_1 = \begin{bmatrix} -5{,}4 & 6{,}4 \\ 6{,}4 & -5{,}4 \end{bmatrix}$ ✓

2) u_1 & u_3:

$G_{s-s_2} = \begin{bmatrix} 0{,}9 & -1 \\ 0{,}4 & -0{,}2 \end{bmatrix} \Rightarrow RGA_2 = \begin{bmatrix} -0{,}818 & 1{,}818 \\ 1{,}818 & -0{,}818 \end{bmatrix}$ ✓ (A)

(b) Which input combination do you recommend and what pairing?

3) u_2 & u_3:

$G_{s-s_3} = \begin{bmatrix} 0{,}8 & -1 \\ 0{,}3 & -0{,}2 \end{bmatrix} \Rightarrow RGA_3 = \begin{bmatrix} -1{,}143 & 2{,}143 \\ 2{,}143 & -1{,}143 \end{bmatrix}$ ✓ (B)

✓

Based on the previous question, I ~~recommend~~ could recommend to pair y_1 with u_3 and y_2 with u_1. (A)
The steady-state RGA (interaction and sensitive measurement) leads to value the closest to one and higher than zero.

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However, the control of y_2 by u_1 will be delayed when we look at the dynamics.
I ~~[illegible]~~ could recommend to pair y_1 with u_3 and y_2 with u_2 as well. (B)

If we look at $g_{u_1 \to y_2}$: $0{,}4 \dfrac{e^{-2s}}{(5s+1)} \simeq 0{,}4 \dfrac{1}{(5s+1)(2s+1)}$

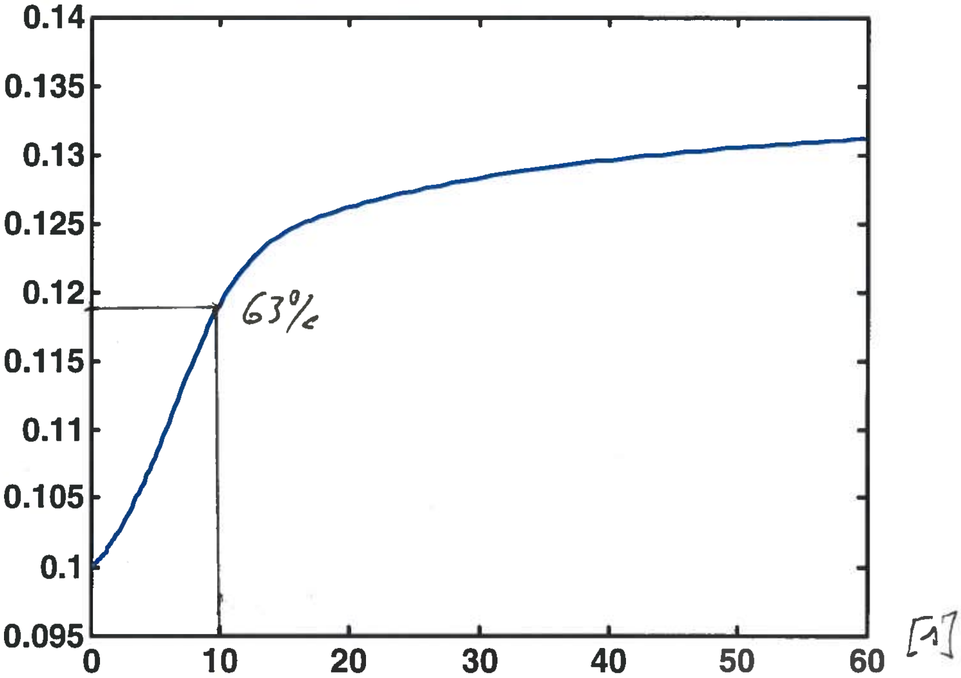
We find the transfered function more acceptable* compared to $g_{u_2 \to y_2}$: $\dfrac{0{,}3}{(5s+1)(3s+1)}$ (> 2)

So, my final answer will be (A), the delay seems to be not so high.

*: high gain, smaller time constants.

Problem 4. (15%)

We have performed an open-loop step response experiment. The figure shows the response in y to a change in the input (u) = 0.1 at t= -0.5 (NOTE!! NOT at t=0). The system is at steady-state before we make this change. Suggest PI-tunings for (1) τ_c=10,. (2) $\tau_c=\theta$.



Identification of a simple first-order model: $\left(G = \frac{k e^{-\theta s}}{(\tau_1 s+1)} \right)$

$\theta = 0{,}5$ + ? 2nd order.

$\tau_1 = 10$ [s]

$k = \frac{0{,}03}{0{,}1} = 0{,}3$

SIMC tuning method: $K_c = \frac{\tau_1}{k} \frac{1}{(\tau_c+\theta)}$

$= \frac{10}{0{,}3} \frac{1}{(0{,}5+\tau_c)}$

$\tau_I = \min(\tau_1, 4(\tau_c+\theta))$

$= \min(10, 2+4\tau_c)$

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If $\tau_c = 10$: $K_c = 3{,}175$ and $\tau_I = 10$ [s]

~~If $\tau_c = 2$: $K_c = 13{,}333$ and $\tau_I = 10$~~

OK

If $\tau_c = \theta = 0{,}5$: $K_c = 33{,}333$ and $\tau_I = 4$ [s] (maybe take θ a bit larger in this case)

Problem 5 (30%)

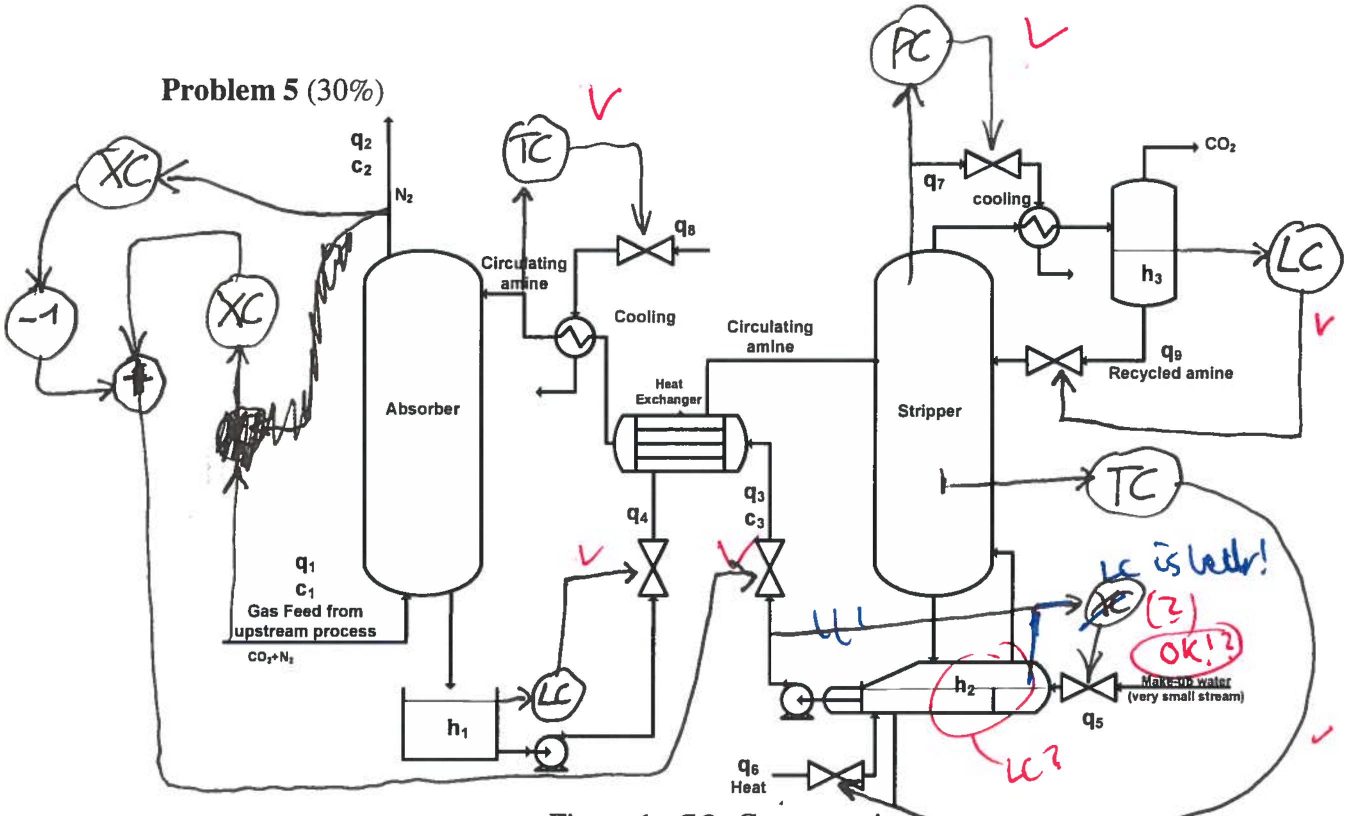

Figure 1. CO_2 Capture unit

The flowsheet of an absorber-stripper process for removing CO_2 from flue gas is shown in Figure 1. In the "cold" absorber (left), CO_2 (which has feed concentration c_1) is absorbed into the amine solution and it is released in the "hot" stripper column (right). The stripper column reboiler is heated with steam (q_6) and and the column is cooled with cooling water (q_7). The circulating amine q_3 is cooled to 40°C by cooling water (q_8) before entering the top of absorber. The pressure at the top of the stripper should be 1 bar. The concentration (c_2) of CO_2 that is released to the air should be less than 1%. Loss of water is compensated by the stream q_5.

(a) Define an economic objective for the process when you get paid for the amount of CO2 leaving the stripper.

5/5

$$J = q_6 \cdot c_{steam} + W_{pumps} - q_1(c_1 - c_2) \cdot c_{CO_2\,captured}$$

with c_{steam}: cost per unit of steam; c_{CO_2}: cost per amount CO_2 captured.

(b) What are the degrees of freedom (dynamically, at steady-state)?

5/5

We assume gas feed is given (no DOF).
Dynamically: 7 DOFs (number of valves) $\{q_3, q_4, q_5, q_6, q_7, q_8, q_9\}$
Steady-state: 4 DOFs (q_3, q_6, q_7, q_8)

(c) What are the steady-state controlled variables? Suggest possible self-optimizing variable(s).

5/5

- The percentage of CO_2 being captured (active constraint)
- The pressure in the stripper (active constraint)
- A temperature inside the stripper (self-optimizing variable)
- The temperature of the amine (should be a known optimized value).

(d) What is meant by "consistency" of and "local-consistency" of inventory control? Discuss the inventory control loops for liquid and gas inventory.

An inventory control is said to consistent when ~~every part of~~ every part of the process is regulated by its in or out-flow. It is local-consistent when every single part of the process is {directly (locally) regulated by its in or out-flow.

4.5

If the TPM is the gas feed, inventory control for liquid and gas is consistent (cf. e)

(e) Suggest a control structure involving feedback loops and draw them on the flow sheet.
(Hint: They should involve LC, TC, XC (where X denotes composition) and PC.)

Cf. Flowsheet.

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(f) Assume that we want maximum throughput (of gas feed). What are possible expected active constraints when the gas load in the absorber is not the problem? Describe a typical control structure that may result. Could MPC be used?

Possible expected active constraints:

- Pressure maximum in the stripper. ✓
- Reboiler duty at maximum. ✓
- Percentage of CO_2 captured at minimum. ✓

5/5

Yes, MPC can be used, it handles better the constraints. As a multivariable controller, MPC will be able to modify the control in a optimal way when some inputs reache saturation.

We can use MPC to control the temperature in the stripper and the percentage of CO_2 being captured (as done in the exercises), the other variables stays in the regulatory layer (PID control).