NTNU – Trondheim
Norwegian University of
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Department of Chemical Engineering

Exam paper for TKP4140 – Process Control

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Examination date: 09 December 2019

Examination time (from-to): 15:00 – 19:00

Permitted examination support material: One (1) A4 double-sided piece of paper with your handwritten notes. Standard calculator.

Other information: State clearly all assumptions you make. You may answer in Norwegian or English

Language: English

Number of pages (front page excluded): 5 (including Bode paper which may be handed in)

Informasjon om trykking av eksamensoppgave

Originalen er:

1-sidig ☐ **2-sidig** ☐

sort/hvit ☐ **farger** ☐

skal ha flervalgskjema ☐

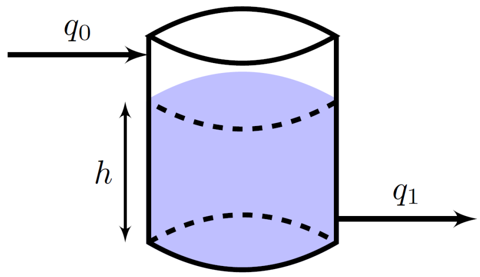
Checked by:

Date Signature

Problem 1 – Modelling and linearization of level (20 %)

Consider the cylindric tank with liquid inflow q_0 [m^3/min] and one liquid outflow q_1 [m^3/min]. The outflow is proportional to the level h [m] and is given by $q_1 = k\ h$ (this could be either because of self-regulation or because we use a P-controller for level).

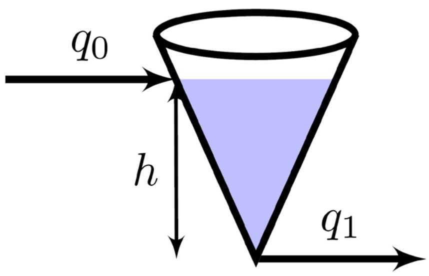
(a) (15%) Assume the area A [m^2] of the tank is constant, as shown in the figure below. (i) Formulate the mass balance, (ii) find the nominal steady-state value of the level and volume (see data below), (iii) linearize the equations and (iv) find the transfer function t(s) from q_0 to h around the nominal steady state.



Cylindric tank with constant area A

Data: A= 10 m^2, q_1 = k h , k= 0.02 m^2/s. Nominal inflow: q_0 = 0.1 m3/s.

(a) (5%) In reality, the tank is conic as shown below, and the area is proportional with the square of the level. Do the same as above, (i-iv), for this case.



Conic tank with varying area A(h)

Data: A(h)=0.4 h^2 , q_1 = k h, k= 0.02 m^2/s. Nominal inflow: q_0 = 0.1 m3/s. Tank volume: $V(h) = \int_0^h A(h)dh$

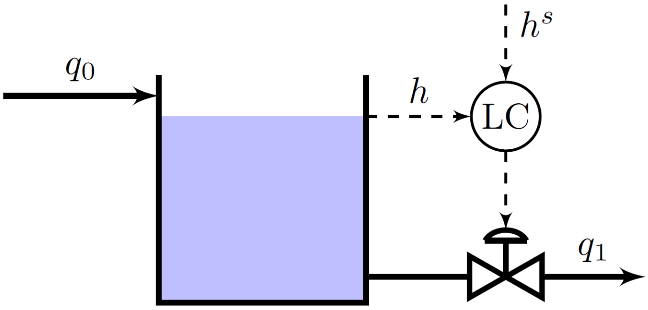
Problem 2 – Level control (20 %)

Consider the tank with one inflow q_0 (disturbance) and one outflow q_1 (input, MV), shown in the figure below. The level h is controlled using a P-controller and the closed-loop time constant is 0.5 [min].

(a) (5%) The closed-loop response from the disturbance q_0 to the input q_1 is then $q_1 = \frac{1}{0.5s+1} q_0$. Explain why this is correct (why is the gain 1 and the time constant 0.5?).

(b) (5%) Sketch the response for q_1 to a unit step change in q_0 of magnitude 1.

(c) (10%) Sketch the response $q_1(t)$ to a sinusoidal disturbance in the flow q_0 of magnitude ± 1 and frequency $\omega = 4\ [\frac{rad}{min}]$, that is, $q_0(t) = \sin(\omega t)$. In particular, what is the period of the oscillations and what is the magnitude of the variations in q_1?



Problem 3 – Controller tuning (30 %)

Consider a process y(s) = g(s)u(s) + g_d(s)d(s), with

$$g(s) = \frac{3}{(2s+1)(0.5s+1)^2},$$
$$g_d(s) = \frac{10}{(2s+1)}$$

We use feedback control and the measurement transfer function for the output y is

$$g_m(s) = \frac{e^{-3s}}{(1.5s+1)}$$

(a) (5%) Make a block diagram of the system (with symbols only)
(b) (10%) Derive a PI-controller c(s) for "tight" control using the SIMC-rules. Note that feedback control is based on the measurement of y.
(c) Consider the closed-loop response for the output y(s) (not the measurement) to a change in the disturbance d, y(s) = T_d(s) d.
- (5%) First derive an expression for T_d(s) with symbols only
- (2%) Put the transfer function expressions into T_d (s) and simplify a little.
- (3%) Sketch the response in y to a step change in d of magnitude 1, both without control and with PI-control.

(d) (5%) Would you recommend using feedforward control? Explain your answer. You can assume for simplicity that the disturbance can be perfectly measured.

Problem 4 – Discrete PI-controller (10 %)

We have a continuous PI-controller u(s) = C(s) e(s) where e=(y_s-y) and $C(s) = K_C\left(1+\frac{1}{\tau_I s}\right)$. However, we want to implement it using a discrete PI-controller.

(a) (3%) How can the PI-controller be expressed in the continuous time domain? That is, write an expression for u(t) as a function e(t).
(b) (3%) Make a plot of a typical time response for discrete control. That is, make a plot of typical continuous signals u(t) and y(t) and show on this plot the discretized values u_k, u_{k-1}, u_{k-2}, and y_k, y_{k-1}, y_{k-2}. Also show the sampling time Δt. What is k?
(c) (4%) The discrete PI-controller can be realized as

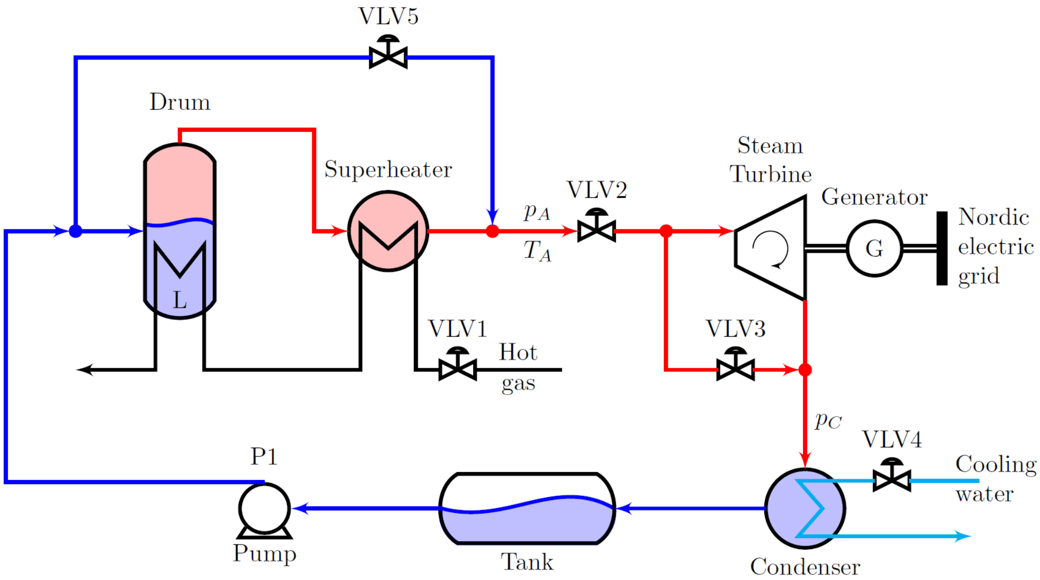
Integrator (bias update): $\bar{u}_k = \bar{u}_{k-1} + f_1(e_k)\Delta t$
Overall PI-controller: $u_k = \bar{u}_k + f_2(e_k)$

- What is e_k?
- What are $f_1(e_k)$ and $f_2(e_k)$? To find these, discretize the continuous PI-controller from part (a).

Problem 5 – Control of heat-to-power cycle (20 %)

Consider a typical steam heat-to-power cycle as shown below. In this cyclic process, thermal energy from hot gas is converted to mechanical energy in the steam turbine and further converted to electrical energy (W) in the generator.

The water/steam cycle: Liquid water is taken from the tank and boosted by a variable speed pump (so P1 is an MV) and fed to the drum. It is heated from liquid water (blue) to high-pressure superheated steam A (red) by exchanging heat with hot gas (black) in two heat exchangers (drum and superheater). The high-pressure superheated steam (A) is expanded to low-pressure saturated steam in a turbine which drives a generator (G) to produce electric power (W) for the electric grid. The low-pressure steam is condensed with cooling water (CW) in the condenser to produce liquid water, which is returned to the tank. Note that since this is a closed system, one of the two levels (drum and tank) in the cycle should be uncontrolled, and since the largest mass is in the tank, we let this level be uncontrolled.



Steam cycle - water in blue, steam in red, hot gas in black, cooling water in light blue

The control objectives are:

- Keep the electrical power produced at the setpoint ($W = W^{sp} = 100$MW).
- Keep the process stable.
- Keep the temperature of the superheated steam at it's maximum, that is, keep it at the setpoint ($T_A = T^{sp}_A = 529$°C).
- Keep the superheated steam pressure p_A below 100 bar (you may select to always control steam pressure to be safe).
- Minimize the condenser pressure, p_C, that is maximize the use of cooling water.

The turbine frequency is fixed (disturbance), which means that there are no degrees of freedom related to the turbine. Note that it is desirable in terms of efficiency (but not necessarily possible if we want to meet all the control objectives) to keep all bypasses closed (i.e. VLV3 and VLV5 closed), and to keep the steam valve VLV2 fully open.

The available measurements are: 1. Power in generator (W). 2. Drum level (L). 3. Superheated steam temperature (TA). 4. Steam pressure (p_A). 5. Condenser pressure (p_C). 6. All flows, and additional temperatures if needed.

(a) identify controlled variables (CVs), manipulated variables (MVs) and main disturbances.

(b) Propose a control structure based on feedback (you can write on this page and hand in)

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