University of South-Eastern Norway

Solution to exam in PEF3006 Process Control

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Solution to Problem 1 (15%)

The tank with pump is an "integrator process". We may use the Skogestad PI settings for "integrator with time-delay" processes, cf. the pertinent table in the appendix of the exam text, but with the time-delay set to zero. The PI settings become

$$K_c = 1/(K_i*T_c)$$

$$T_i = 2*T_c$$

where K_i is the normalized slope of the step response in the process output variable, here the level. (K_i is also the integrator gain.) Assuming the control signal is a step from 0 to U, the slope can be calculated from the process model as

$$dh/dt = S = - U/A \text{ [m/s]}$$

giving

$$K_i = S/U = - 1/A$$

which gives the folliwing PI settings:

$$K_c = 1/(K_i*T_c) = - A/T_c$$

$$T_i = 2*T_c$$

Here we use

$$T_c = A*\Delta h_{max}/\Delta F_{in} = 2000*0.5/1 = 1000 \text{ s}$$

giving

$$\underline{\underline{K_c = - A/T_c = - 2000/1000 = - 2 \text{ m}^2/\text{s}}}$$

$$\underline{\underline{T_i = 2*T_c = 2*1000 \text{ s} = 2000 \text{ s}}}$$

Solution to Problem 2 (30%)

a (10%) The tank with pump is an "integrator with time-delay" process with

$$K_i = S/U = - 1/A$$

as derived in Problem 1 (the derivation is therefore not repeated here). The Skogestad PI settings for an integrator with time-delay process are:

$$K_c = 1/[K_i*(T_c + \tau)] = 1/(2*K_i*\tau) = - A/(2*\tau) = - 2000/(2*10) = - 100\ m^2/2$$

$$T_i = 4*\tau = 4*10 = 40\ s$$

b (10%) Substituting the process output variable in the process model by its setpoint and then solving the process model for the control signal, gives the feedforward controller:

$$u_{ff} = F_{in} - A*dh_{sp}/dt$$

c (5%)

Alternative answer #1: Assume that the level increases slightly relative to the setpoint. To bring the level back to the setpoint, the control signal, and the pump flow, must increase. In other words, the situation is "measurement up - control signal up", which indicates direct action mode.

Alternative answer #2: The controller gain is negative, implying direct action mode.

d (5%) A flow control loop of the pump should be implemented as the secondary loop, inside the primary level control loop, comprising a cascade control system see Figure 1.

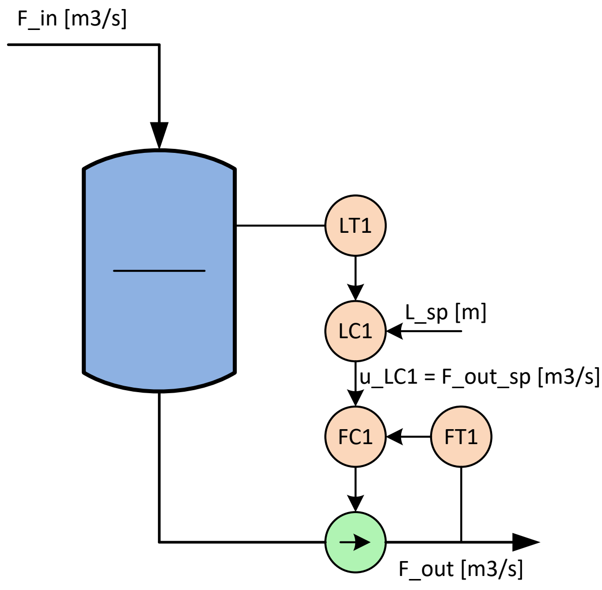

Figure 1

Solution to Problem 3 (10%)

The MPC is a model-based controller that, continuously predicts the optimal future control sequence using the following information:

- An optimization criterion that typically consists of a sum of future (predicted) squared control errors and quadratic control signal changes.
- A process model
- The current process state obtained from measurements and/or state estimates from a state estimator which typically is in the form of a Kalman filter.
- Current, and, if available, future setpoint values and process disturbance values.
- Constraints (max and min values) of the control signal and the process variable.

From the optimal future control sequence, the first element is picked out and applied as control signal to the process. The above calculations are repeated at the next point of time (i.e. “continuously”).

Some versions of the MPC assume linear process models, while others are based on nonlinear process models. The models may be multivariable and contain time-delays.

Figure 2 illustrates the behaviour of the MPC.

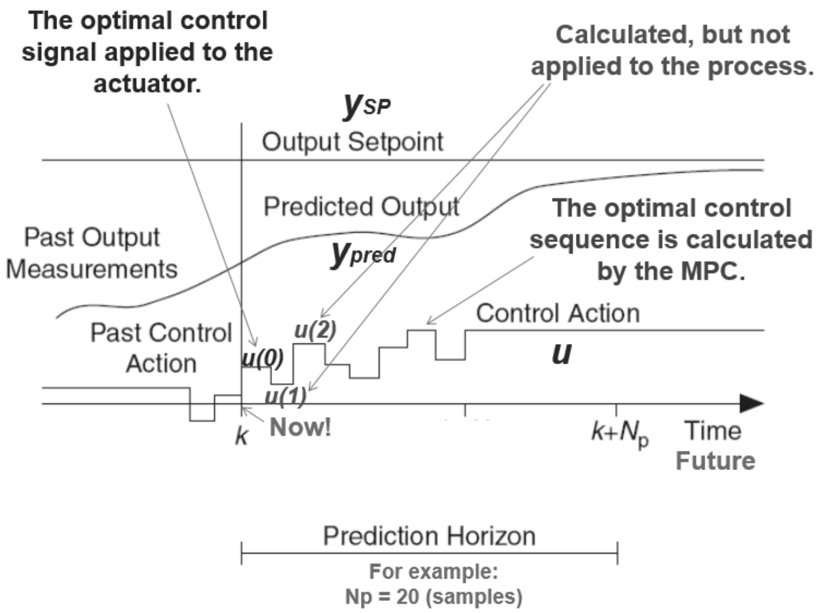

Figure 2

The state estimator is important because the current process state (the state “now”) that it estimates, is used by the MPC optimizer as the *initial state* for the predictions (or simultions) of the future states, over the prediction horizon. The state estimate may include unmeasured disturbances and/or unknown model parameters.

Solution to Problem 4 (5%)

We can use the “repeated Ziegler-Nichols’ method”:

$$\underline{\underline{K_c = 0.45*2 = 0.9}}$$

$$\underline{\underline{T_i = T_p/1.2 = 1.5/1.2 = 1.25 \text{ d}}}$$

where T_p is found as shown in Figure 3.

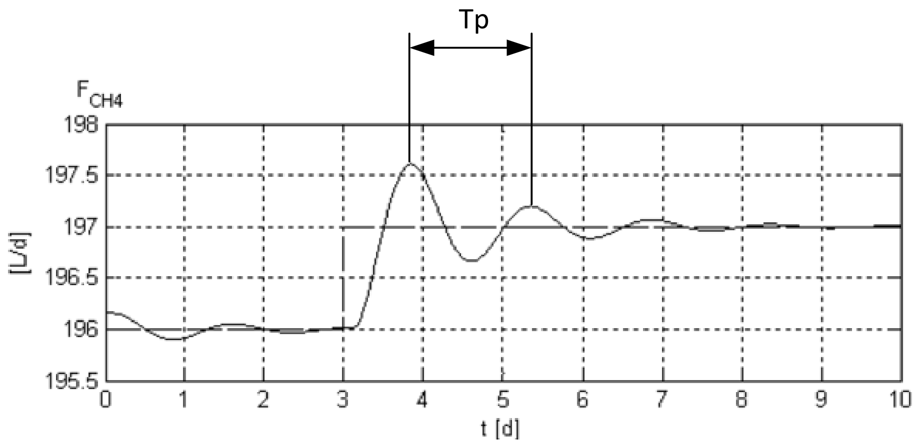

Figure 3

Solution to Problem 5 (5%)

The (three) main elements of a sequential function chart (SFC) are:

- Steps defines the possible states of the control system. A step is either active or passive. Example: The filling step of a batch reactor.
- Actions of a step are the control actions executed by the control device (typically a PLC), e.g. opening a valve, when that step is active.
  Example: Setting the inlet valve of a batch reactor in the open position.
- Transitions are the jumps from presently active steps to their next steps. A transition from an active step to a next step takes place once the transition condition is satisfied, e.g. once a button has been pressed, or once the level in a tank has passed a certain value.
  Example: The level of the material in a batch reactor is equal to or larger than to its high limit.

Figure 4 shows an SFC (this SFC is a complete one, however, an uncomplete chart is accepted as an answer).

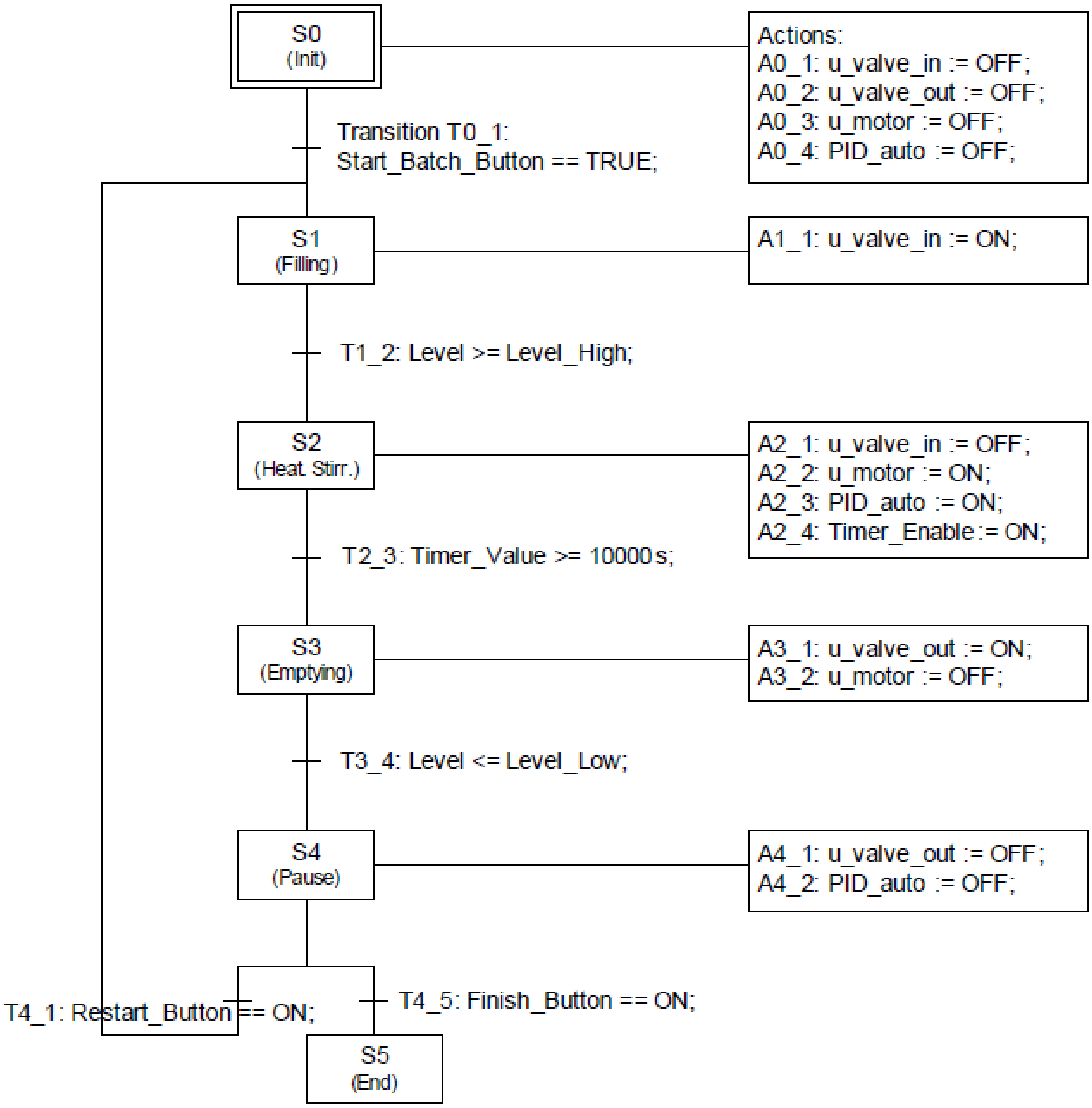

Figure 4

Solution to Problem 6 (5%)

PI controllers are more often used than PID controllers in practical control systems because the derivative term propagates measurement noise, causing the control signal to become noisy, which may cause excessive wear of the actuator.

PI controllers are more often used than P controllers in practical control systems because the integral term ensures zero steady-state control error, while this error, for most processes, is non-zero without integral term as in a P controller.

Solution to Problem 7 (10%)

Taking the Laplace-transform of both sides of the PID controller function, which is shown in the appendix of the exam text, gives the transfer function H(s) as indicated:

$$
\begin{aligned}
u(s) &= \frac{u_0}{s} + K_p e(s) + \frac{K_p}{T_i}\frac{1}{s}e(s) + K_p T_d \left[se(s) - e_0\right] \\
&= \frac{u_0}{s} + \underbrace{\left[K_p + \frac{K_p}{T_i}\frac{1}{s} + K_p T_d s\right]}_{H(s)} e(s) - K_p T_d e_0
\end{aligned}
$$

Comment: Here it is assumed that u_0 is a constant. However, u_0 could also have been neglected (assumed zero) when deriving the transfer function from e to u since it does not affect this transfer function. Also, the initial value of the control error, e_0, could have been neglected (assumed zero) for the same reason.

Solution to Problem 8 (20%)

Figure 5 shows one possible solution (the same as in the textbook). The dashed signal lines of the quality control loop assumed that an online production quality sensor is available (which, however, is often not the case).

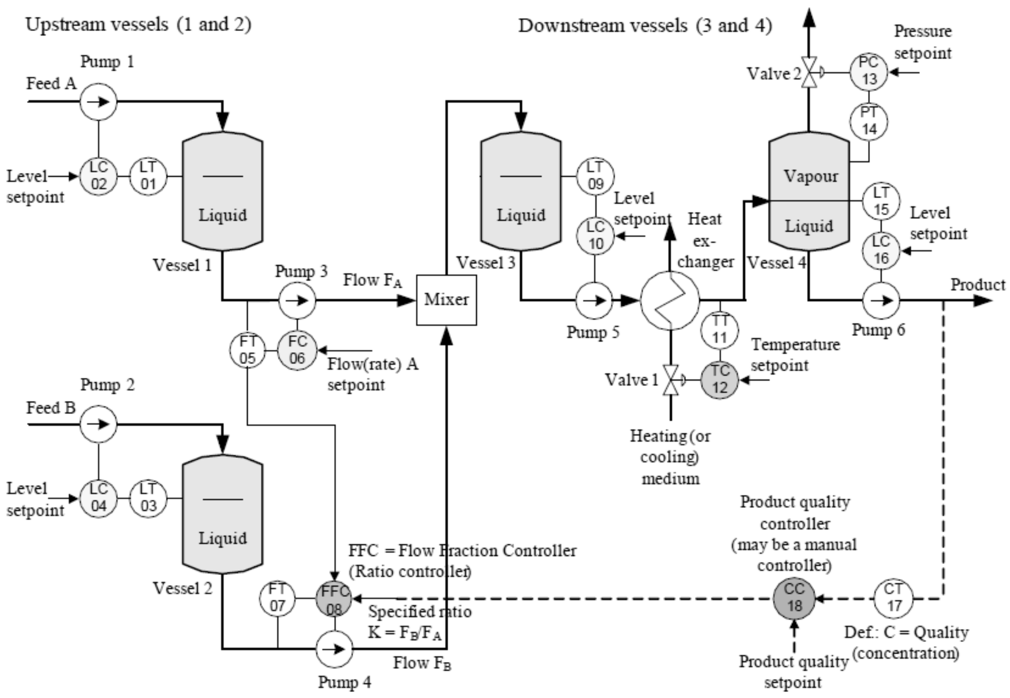

Figure 5