University College
of Southeast Norway

Solution to exam in PEF3006 Process Control

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Solution to Problem 1 (20%)

a (2%) Replacing F_{out} in the process model by $u = K_c(h_{sp} - h)$ gives

$$A\frac{dh}{dt} = F_{in} - F_{out} = F_{in} - u = F_{in} - K_c(h_{sp} - h)$$

which is the model of the level control system.

b (5%) At static conditions, the time-derivatives are zero. Thus, the static model of the level control system is

$$0 = F_{in} - K_c(h_{sp} - h)$$

Solving for h_s gives

$$h_s = h_{sp} - \frac{F_{in}}{K_c}$$

c (5%) Taking the Laplace transform of the above differential equation which comprises the control system model, gives

$$A[sh(s) - h_0] = F_{in}(s) - K_c\left[h_{sp}(s) - h(s)\right]$$

Here we can set the initial value h_0 equal to zero, and furthermore, assume that F_{in} is zero since these two quantities do not affect the transfer function from h_{sp} to h. Thus,

$$Ash(s) = -K_c\left[h_{sp}(s) - h(s)\right]$$

from which we get

$$\frac{h(s)}{h_{sp}(s)} = \frac{-K_c}{As - K_c} = M(s)$$

d (4%) Writing $M(s)$ on the standard form of time-constant systems:

$$M(s) = \frac{K}{Ts + 1} = \frac{-K_c}{As - K_c} = \frac{1}{(-A/K_c)s + 1}$$

Thus, the time-constant of the control system is

$$T_c = -\frac{A}{K_c}$$

e (2%) The pole is the root of the characteristic equation which is

$$As - K_c = 0$$

Thus, the pole is

$$s = p = \frac{K_c}{A}$$

f (2%)

Solution alternative 1: For the pole to have a strictly negative real part, K_c must be negative (i.e. direct action controller mode).

Solution alternative 2: Generally, for a control system to be stable, the controller must have correct action mode (reverse mode or direct mode), dependent of the process to be controlled. For the level control system: 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, i.e. negative controller gain.

Solution to Problem 2 (10%)

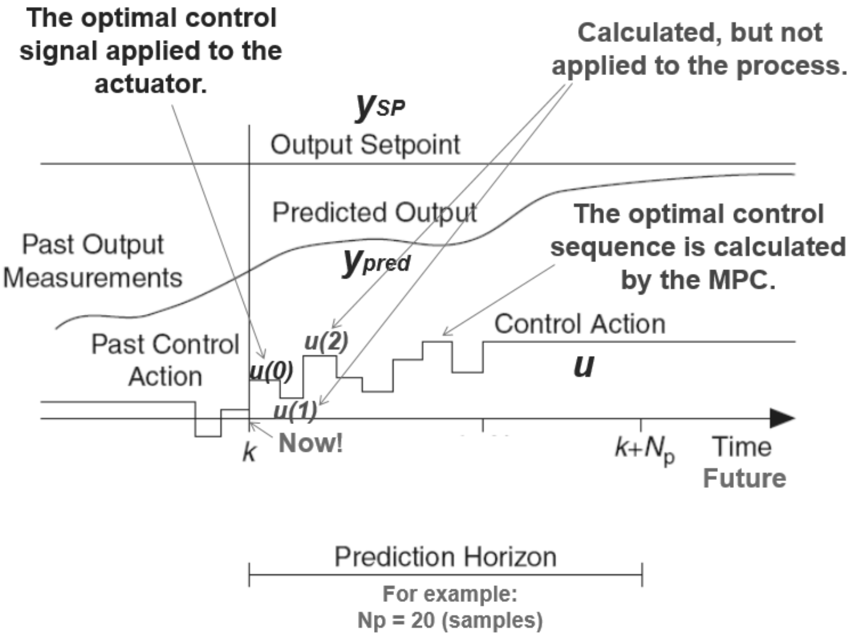
The MPC is a model-based controller that, continuously predicts the optimal future control sequence using the following information:

- 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.

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 1 illustrates the behaviour of the MPC.



Figur 1

The state estimator is important because the current process state that it calculates is used as the initial state of the prediction of the future states.

Solution to Problem 3 (5%)

The purpose of ratio control is to control a mass flow, say F2, so that the ratio between this flow and another flow, say F1, is F2 = K*F1 where K is a specified ratio.

Figure 2 shows at the left the structure of a ratio control system in detail, and at the right compact but equivalent representation of ratio control with the symbol FFC (Flow Fraction Controller).

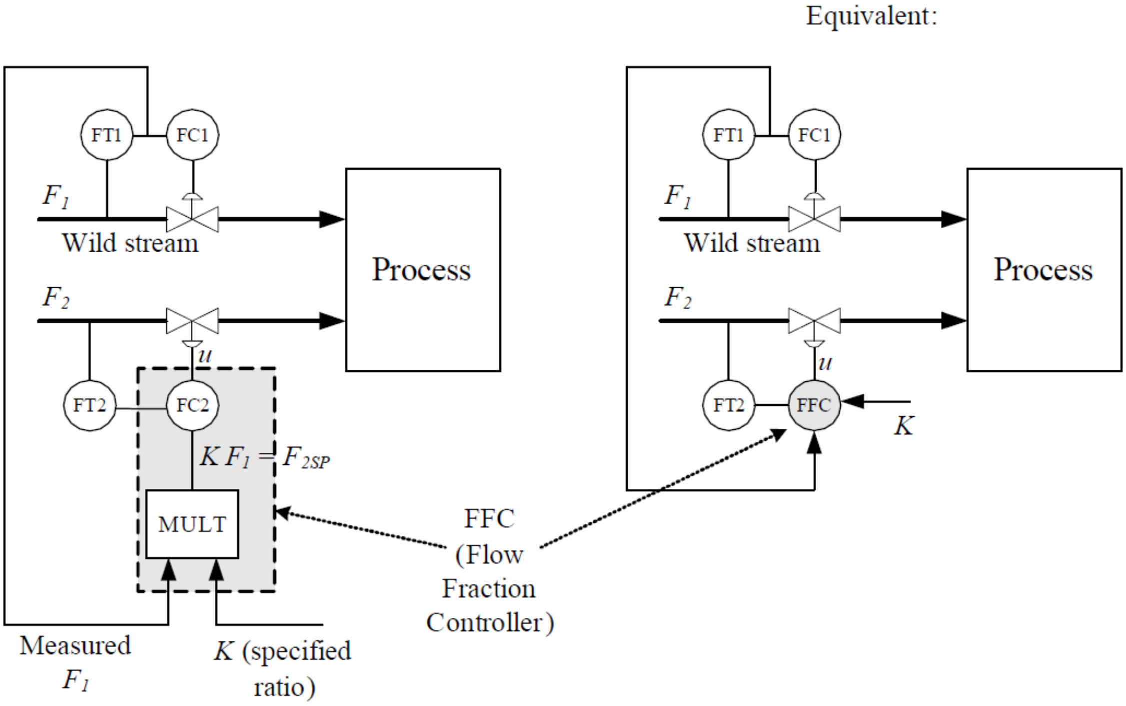


Figure 2

Example: Optimal operating condition of a burner requires a specified ratio between oil inflow and air inflow. This ratio can be obtained with ratio control: For any given oil flow, the air flow is automatically adjusted so that the ratio between the two flows are as specified.

Solution to Problem 4 (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 3 shows an SFC (this SFC is a complete one, however, an uncomplete chart is accepted as an answer).

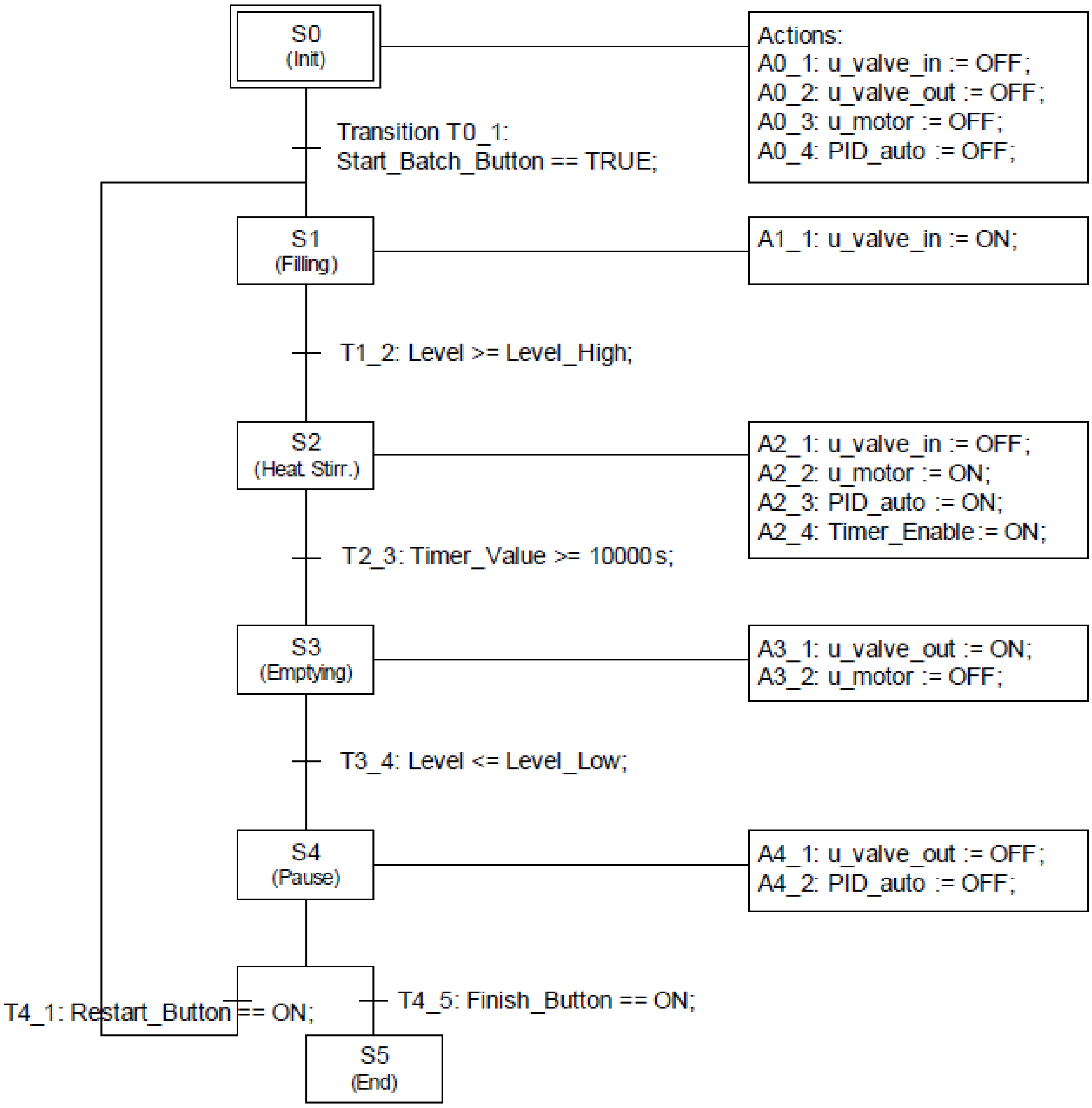


Figure 3

Solution to Problem 5 (5%)

The Skogestad method for process dynamics assumed as "integrator with time-delay". The hand-rule of Tc = tau = 1 min is used. The integrator gain, which is the same as the normalized slope of the step response, is

$$Ki = S/U = (10\ \%/\text{min})/20\ \% = 0.5\ \text{min}^{-1}$$

The PI settings become

$$Kc = 1/(2*Ki*tau) = 1/(2*0.5\ \text{min}^{-1}*1\ \text{min}) = 1$$

$$Ti = 4*tau = 4*1\ \text{min} = 4\ \text{min}$$

Solution to Problem 6 (5%)

The Ziegler-Nichols method is used for the tuning. The ultimate gain is Kpu = 2, and the ultimate period is Pu = 60 s. The PI settings become

$$Kp = 0.45*Kpu = 0.45 *2 = 0.9$$

$$Ti = Pu/1.2 = 60\ s/1.2 = 50\ s$$

Solution to Problem 7 (5%)

The D-term typically gives a noisy control signal. The measurement filter attenuates measurement noise, and thereby reduces control signal noise. Thus:

- Time interval 1: PID controller without filter.
- Time interval 2: PID controller with filter.
- Time interval 3: PI controller with filter.

Solution to Problem 8 (10%)

a (7%) Feedforward control is a control method where there is a coupling from the setpoint and/or from the disturbance directly to the control variable. The purpose of feedforward control is to obtain an improved compensation for disturbances and improved setpoint tracking compared with feedback control. Feedforward control is typically used together with feedback control. Figure 4 shows the structure of a control system with both feedforward and feedback control. The purpose of feedback control is to reduce the control error due to the inevitable imperfect feedforward control. Practical feedforward control can never be perfect, because of model errors and imprecise measurements.

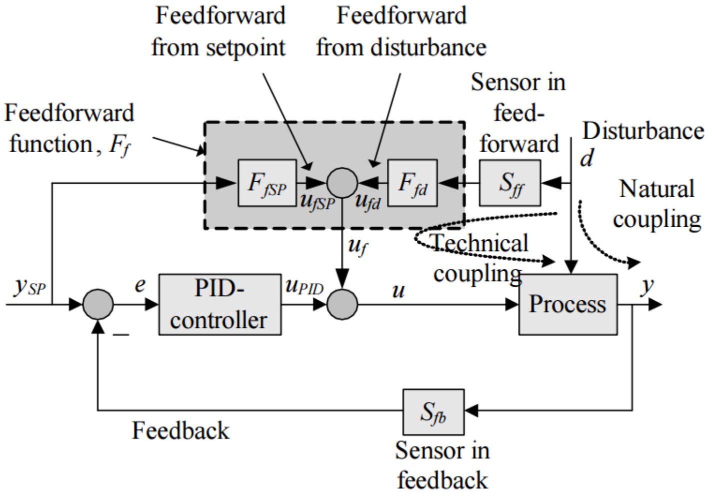


Figure 4

b (3%) Examples of process disturbances:

- Ambient or environmental temperature of e.g. a reactor.
- Inlet temperature to e.g. a reactor or an heat exchanger.
- Inlet flow to e.g. a reactor or an heat exchanger.

- Wind force acting on a ship.
- Water current force acting on a ship.

Solution to Problem 9 (10%)

See Figure 5.

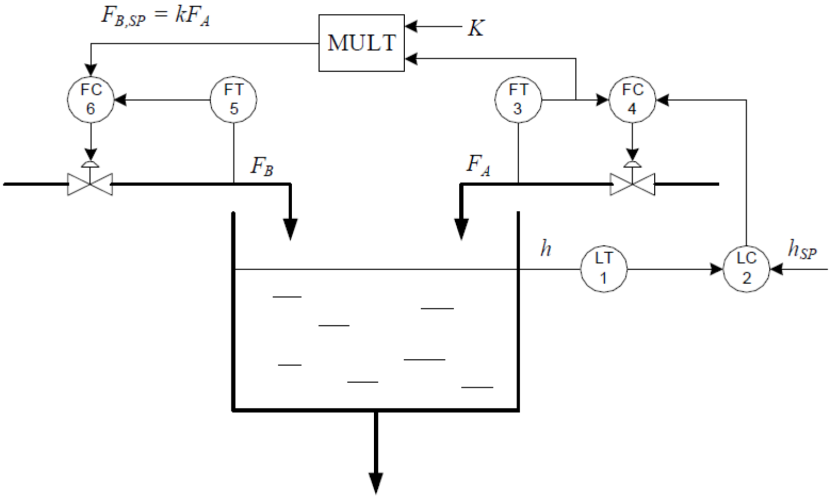


Figure 5

Solution to Problem 10 (5%)

Assume that the process measurement is equal to the setpoint initially, and that for any reason the process measurement increases to become larger than the setpoint (this change may for example have been caused by a change of the process disturbance). If the controller must decrease the control signal to bring the increased process measurement back to the setpoint, the controller shall have Reverse action mode. If the controller must increase the control signal to bring the increased process measurement back to the setpoint, the controller shall have Direct action mode.

Example: Figure 6 shows the control system. It is assumed that the valve is a Fail Closed valve, i.e. when the control signal is reduced, the valve opening is reduced, and, hence the flow is reduced — and vice versa. Assume that the level is at the setpoint initially, and that the level then (for any reason) increases. How should the control signal acting on the pump be adjusted to get the level back to the setpoint? The outflow must be increased. With the given valve, increased flow is obtained with an increased control signal. Hence, this case is an “up-up” case, and therefore the controller must have direct action.

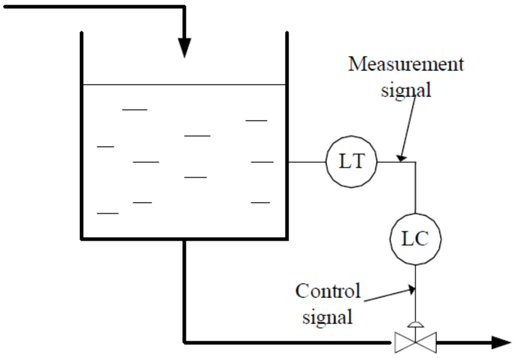


Figure 6

Solution to Problem 11 (20%)

Figure 7 shows a possible solution (the same figure as in the textbook). The dashed signal lines of the quality control loop assumed that an online production quality sensor is available (which is often not the case).

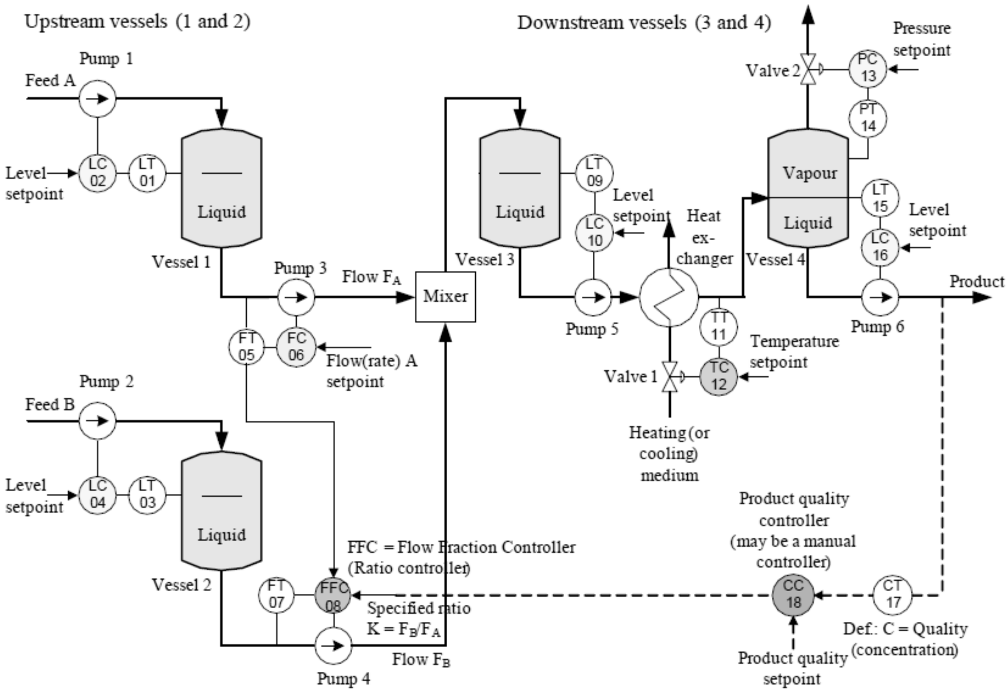


Figure 7