University College of Southeast Norway

Solution to exam in PEF3006 Process Control

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Solution to Problem 1 (10%)

Taking the Laplace-transform of both sides of the PID controller function gives the transfer function H(s) as indicated:

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

Here it is assumed that u0 is a constant. However, u0 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, e0, could have been neglected (assumed zero) for the same reason.

Solution to Problem 2 (10%)

Figure 1 shows a block diagram of a feedback control system.

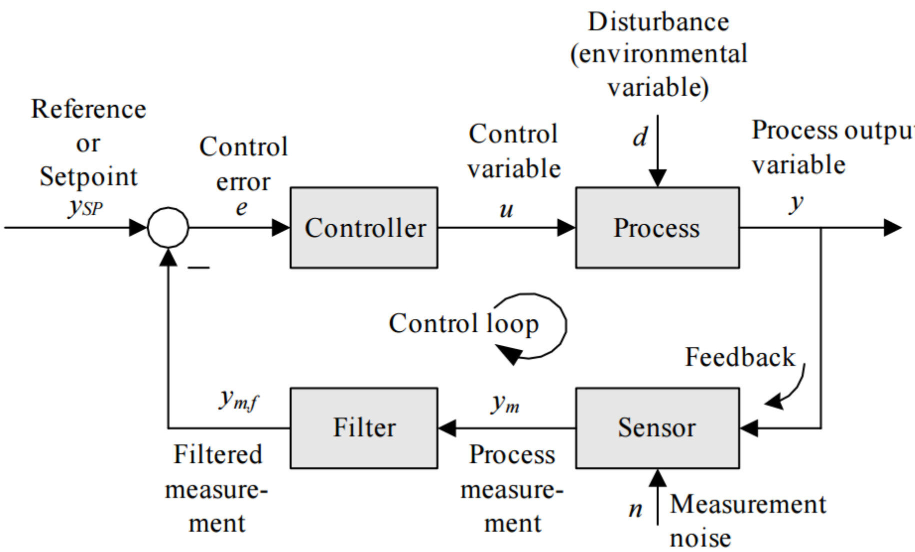

Figure 1

Blocks:

- Process is the physical system to be controlled.

- Sensor measures the process output variable to be controlled.
- Filter attenuates the measurement noise.
- Controller manipulates the process via the actuator.

Signals:

- The control variable or the manipulating variable is the variable which the controller uses to control or manipulate the process.
- The disturbance is a non—controlled input variable to the process which affects the process output variable.
- The setpoint or the reference is the desired or specified value of the process output variable.
- The measurement signal is the output signal from the sensor which measures the process variable.
- The measurement noise is typically a random component in the measurement signal.
- The control error is the difference between the setpoint and the process output variable.

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).

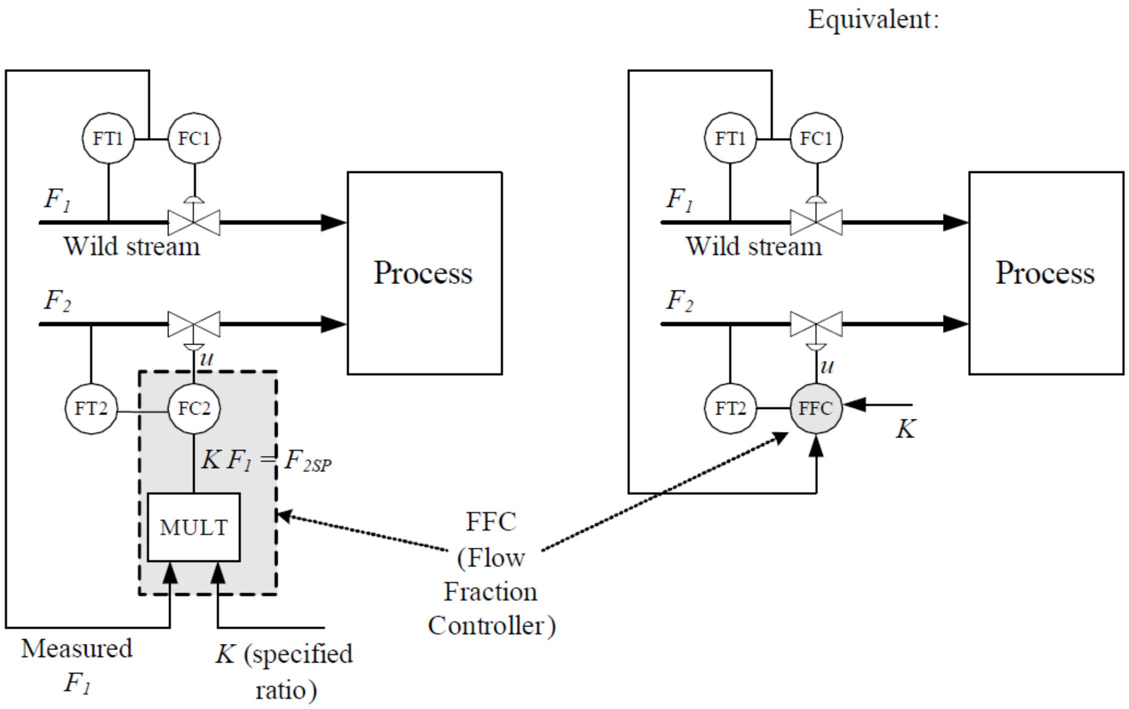

Figure 2

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 (10%)

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 to this exam problem).

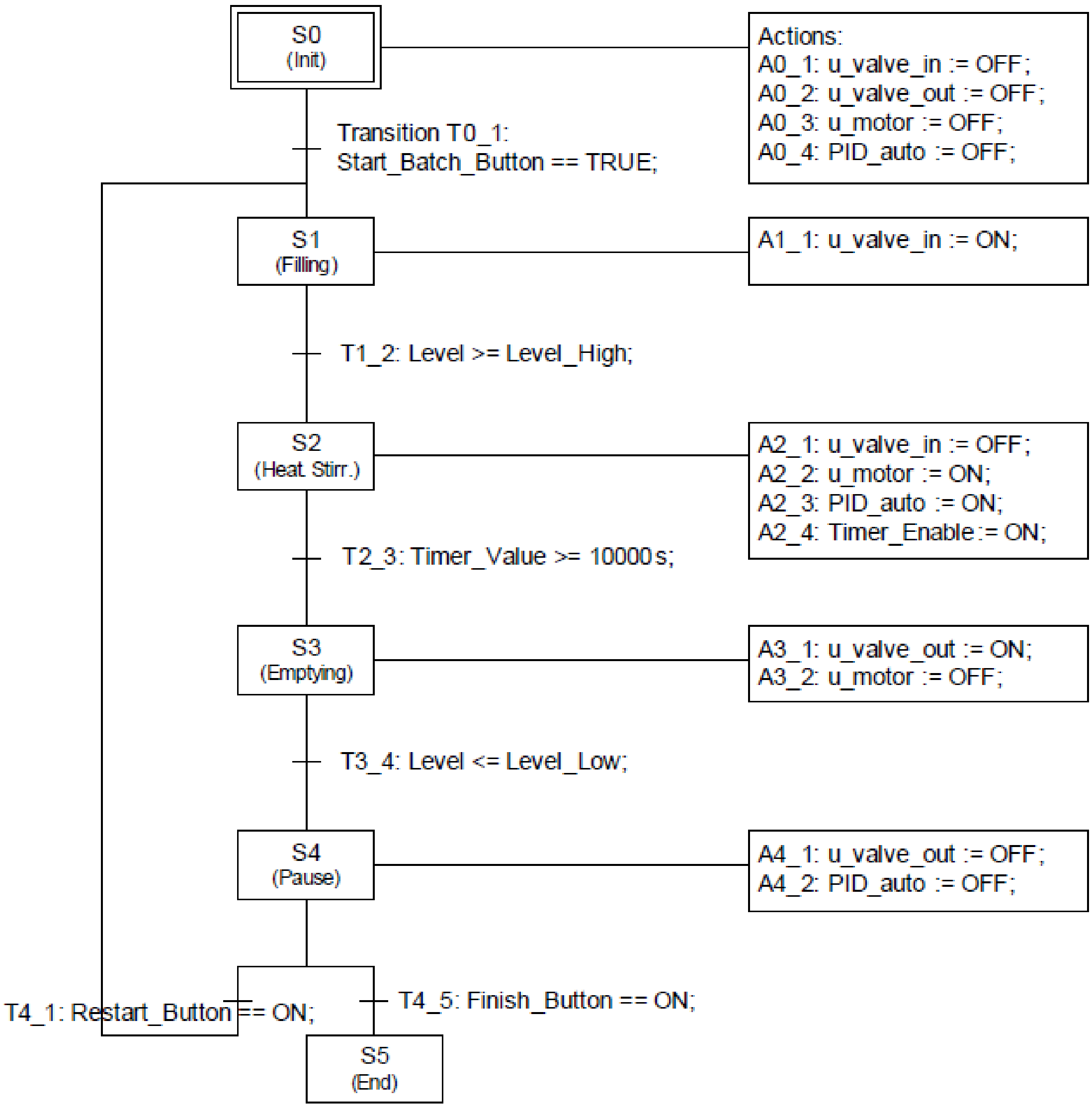

Figure 3

Solution to Problem 5 (10%)

Figure 4 shows the control system which consists of a cascade control and feedforward control from the measured inflow disturbance d_f. The cascade control system has the level control loop as the primary control loop and the speed control loop as the secondary control loop.

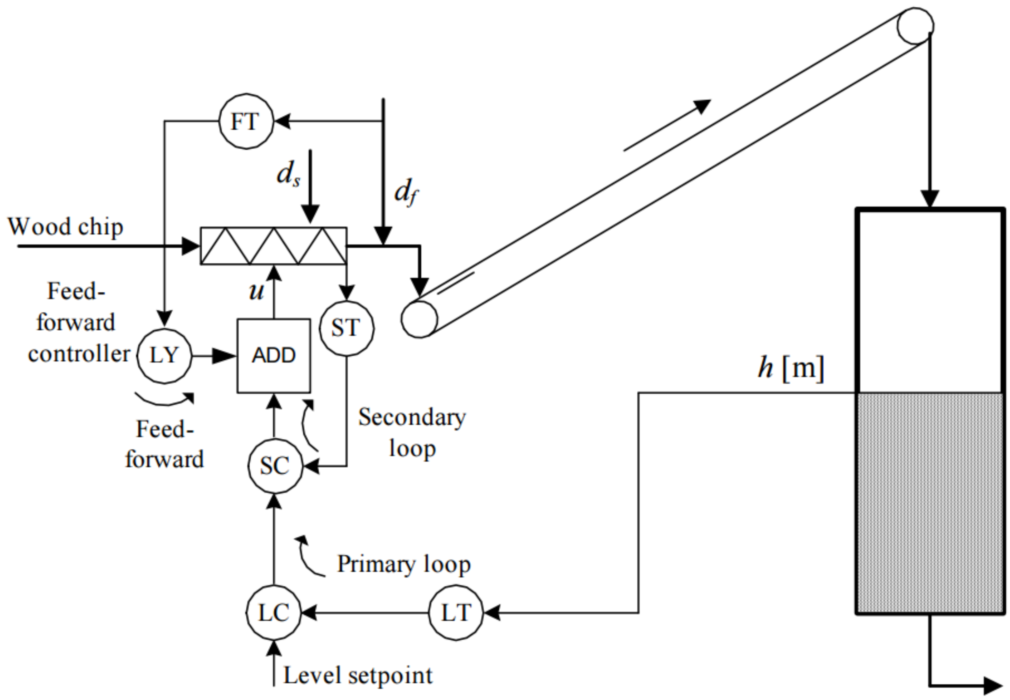

Figure 4

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%) The Ziegler-Nichols method for PI controller tuning: First, bring the process to or close to the normal or specified operation point by adjusting the nominal control signal u_0 (with the controller in manual mode). Then, ensure that the controller is a P controller, i.e. set $T_i = \infty$ (or very large) and $T_d = 0$, with $K_p = 0$. Then, with the controller in automatic mode, increase K_p by trial-and-error to the the value K_{p_u} which causes the the control loop to become marginally stable, i.e. there are sustained oscillations in any signal in the loop. From these oscillations, read off the period, P_u. Then, calculate proper PI settings as $K_p = 0.45 K_{p_u}$ and $T_i = P_u/1.2$ to be applied in the controller.

Acceptable stability of the control system is defined as the step response in the process output variable, with a step in the process disturbance or in the setpoint, showing one quarter decay ratio, see Figure 5.

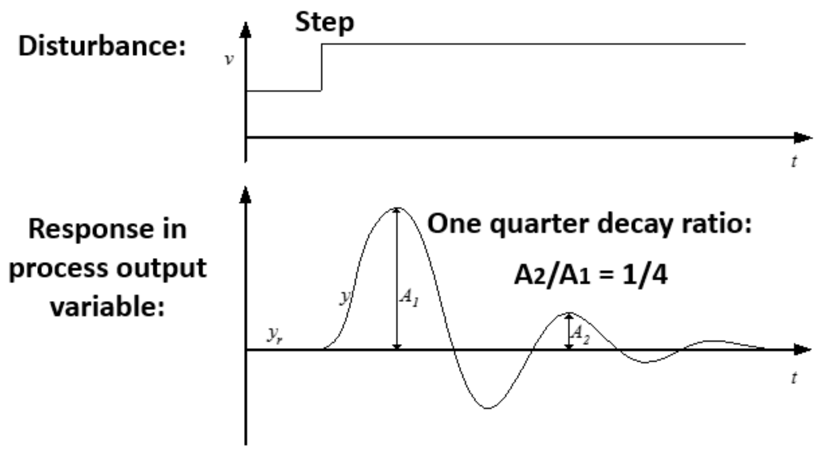

Figure 5

Solution to Problem 8

(10%) The feedforward controller can be derived by substituting θ by its setpoint, θ_{SP}, in the model, Eq. (1), and then solving for the control signal, u. According to the problem formulation, $\tau = 0$. The result is the following formula of the control signal, i.e. the feedforward controller:

$$u_f(t) = \left\{ c\rho V \dot{\theta}_{SP}(t) - c\rho F \left[\theta_{in}(t) - \theta_{SP}(t)\right] - U \left[\theta_e(t) - \theta_{SP}(t)\right] \right\} / K_h$$

The following variables – assuming they are not known by other means – must be measured to make the feedforward controller implementable: F (with a flow sensor), θ_{in} (temperature sensor), and θ_e (temperature sensor). The other quantities, i.e. c, ρ, V, U, and K_h are here assumed known.

Solution to Problem 9 (10%)

It is useful to assume that the PI controller originally is tuned using the Skogestad method assuming «integrator with time-delay » dynamics:

$K_{p0} = 1/(2*K_{i0}*tau_0)$ and $T_{i0} = 4*tau_0$.

An increase of the process gain of factor 3 implies

$K_{i1} = 3*K_{i0}$

An increase of the process time-delay by factor 2 implies

$tau_1 = 2*tau_0$

Thus, the new PI settings become

$$\underline{K_{p1}} = 1/(2*K_{i1}*tau_1) = 1/[2*(3*K_{i0})*(2*tau_0)] = (1/6)*1/(2*K_{i0}*tau_0) = \underline{(1/6)*K_{p0}}$$

and

$$\underline{T_{i1}} = 4*tau_1 = 4*(2*tau_0) = 2*(4*tau_0) = \underline{2*T_{i0}}$$

Solution to Problem 10 (20%)

Figure 6 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).

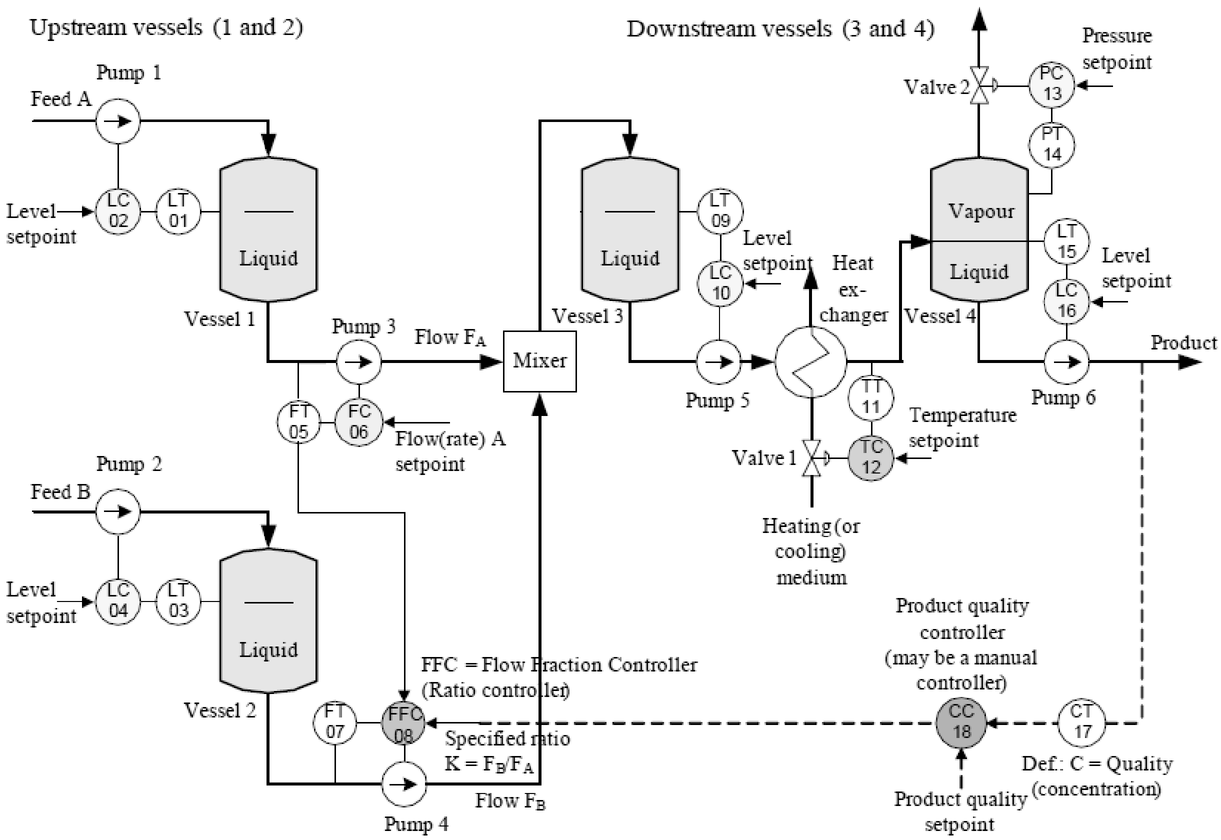

Figure 6