FAULTS DETECTION AND LEVEL CONTROL IN COUPLED TANKS

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Abstract: *This paper presents a mechanism for the detection and localization of faults in a plant, which is equipped with two coupled tanks, using residual methods. The water circuit consists of the upper and lower tanks connected through a system of pipes and valves. The controlled variable is the level in the upper tank. The level control system and the faults detection structure were developed under Matlab Simulink. The faults detection structure allows us to detect two faults that can occur in the plant, separately. The proposed method was theoretically developed and experimentally verified on the plant model.*

Key words: fault detection; level control; residue

1. Introduction

A fault in a dynamical system can often be defined as a deviation from the nominal state in the system parameters or structure [1]. Fault detection is the indication that something is going wrong in the monitored system. It was proposed many different approaches to fault detection based either on the model of the system (analytical methods) [2] or on the knowledge about the system (heuristic methods) [3, 4, 5]. The laboratory plant can be the subject of a series of additive faults and disturbances. The faults and disturbances can appear in processing equipment (example: the breaking of a pipe in the tank) or in auxiliary equipments (example: faults of the actuators and the faults of the transducers). Faults can negatively influence the quality of the production or can damage the machinery or harm humans. Therefore the faults shall be quickly detected and eliminated. In order to detect a fault, we need a reference for the nominal plant operation. This reference can be generated from a plant mathematical model describing the relationship between plant inputs and outputs.

This system has the typical characteristics of tanks, pipelines and pumps used in many industries. In this case, the faults are: the pump is not running completely the command it receives or there may be an additional pressure loss and obturating the flowing section or additional pipeline breakings.

This paper is organized as follows: the system with two tanks is described in section 2, the mathematical model of the plant is presented in section 3, in section 4 is presented the implementation of the faults detection structure and the experimental results, the conclusions are presented in section 5.

2. Description of the plant

The plant is equipped with two tanks of identical quantity, a level transducer with ultrasounds mounted on the superior tank, the variable flow supply pump, local regulator for adjustment of the pumps flow, flow transducer to measure the output flow from the superior tank, and flow transducer to measure the pumps flow at water recalculating in the inferior tank [6, 7].

For the level measurement in the upper tank, the sensor is generating an ultrasonic wave, which is reflected by the water surface and received back by the sensor. The atmospheric air is used as propagation medium for the ultrasonic waves. The sensor output is proportional with the transit time of the ultrasonic wave between the sensor and the water surface and is generated by an electronic module connected to the sensor. The output signal of the sensor is a 4-20 mA current signal, for a variation of level between 0-500 mm [6].

The liquid level control is achieved by changing the water pump flow, using the speed command of the driving motor. This is achieved by varying the supply voltage of the pump using the pump regulator, which is driven with a voltage signal in the range of 2-10 V DC.

The hydraulic system diagram of the plant is shown in Figure1 [7].

The state variables are:

$L_1 = x_1$ the level of the tank1

$L_2 = x_2$ the level of the tank2

The input variables are :

U_c the command to adjust the level in the tank 1

Figure 1: The hydraulic system diagram

The didactics plant allows the level control in the upper tank, using flow's command corresponding to the water's recirculation pump from the lower basin of the upper basin. The disturbance is the flow section of the pipe, between the two tanks.

3. Mathematical models

In order to implement the faults detection diagram it is necessary to determine the mathematical model of the plant as accurate as possible, to emphasize the influence of the faults and the disturbances on observable variables and then the reduction of the processing requirements.

The mathematical model of the system is determined using the mass balance equations [7]:

$$\frac{dL_1}{dt} = \frac{F_p(U_c) - F_2(S_2, L_1)}{A_1} = \frac{k_p U_c - C S_2 \sqrt{L_1}}{A_1} \quad (1)$$

$$\frac{dL_2}{dt} = \frac{F_2(S_2, L_1) - F_3(U_c)}{A_2} = \frac{C S_2 \sqrt{L_1} - k_p U_c}{A_2} \quad (2)$$

Where C is a coefficient depending on the viscosity of the fluid loss and sectional shape of the flowing, S_2 sectional area of the valve transitions between the two tanks, A_1 and A_2 cross-sectional area of the tank1, respectively tank2, F_p is the inflow rate of tank1 and F_2 is the outflow rate from tank2.

In canonical form the mathematical model is:

$$\frac{dL_1}{dt} = -\frac{C}{A_1} S_2 \sqrt{L_1} + \frac{k_p}{A_1} U_c \quad (3)$$

$$\frac{dL_2}{dt} = \frac{C}{A_2} S_2 \sqrt{L_1} - \frac{k_p}{A_2} U_c \quad (4)$$

In steady state:

$$k_p U_{c0} = C S_{20} \sqrt{L_{10}} = F_{20} \quad (5)$$

By linearizing of the equations (3) and (4) around the steady state values, resulting linear form of the mathematical model (6) and (7), which contain the section variation ΔS_2 which can occur only under fault conditions. Under normal conditions $\Delta S_2 = 0$.

$$\Delta \dot{x}_1 = -\frac{CS_{20}}{2A_1\sqrt{L_{10}}}\Delta x_1 + \frac{k_p}{A_1}\Delta U_C - \frac{C\sqrt{L_{10}}}{A_1}\Delta S_2 \quad (6)$$

$$\Delta \dot{x}_2 = \frac{CS_{20}}{2A_2\sqrt{L_{10}}}\Delta x_1 - \frac{k_p}{A_2}\Delta U_C + \frac{C\sqrt{L_{10}}}{A_2}\Delta S_2 \quad (7)$$

Where: $\Delta x_1 = \Delta L_1 = L_1 - L_{10}$; $\Delta x_2 = \Delta L_2 = L_2 - L_{20}$; $x_{10} = L_{10}$ and $x_{20} = L_{20}$

Replacing the coefficient C obtained from equation (5) and applying Laplace transform in zero initial conditions result:

$$\Delta x_1(s) = \frac{1}{Ts+1} \left[\frac{2x_{10}k_p}{F_{20}}\Delta U_C(s) - \frac{2x_{10}}{S_{20}}\Delta S_2(s) \right] \quad (8)$$

$$\Delta x_2(s) = \frac{A_1/A_2}{Ts+1} \left[-\frac{2x_{10}k_p}{F_{20}}\Delta U_C(s) + \frac{2x_{10}}{S_{20}}\Delta S_2(s) \right] \quad (9)$$

Where: $T = \frac{2A_1x_{10}}{F_{20}}$

4. The implementation of the faults detection structure

The method is based on the difference between the real plant with fault and the model without the fault. The input model applies the same command variables as the real plant, so this difference (residue) is influenced both by the faults and the disturbances.

We will analyze the following faults which may occur in the plant:

- the pump is not running completely the command it receives or there may be an additional pressure loss in the upper valve, which is assembled after the pump, and this determines the pump flow to be influenced by the fault, therefore it is no longer proportional to the control voltage;

$$\Delta F_p = k_p(\Delta U_{Cn} + \Delta U_d) \quad (10)$$

Where ΔU_{Cn} is pump control signal and ΔU_d the equivalent in the control signal of the actuator's fault.

- the modification of the flow section S_2 due either to a fluctuation of the flow system, by obturating the flowing section or additional pipeline breakings, which is equivalent to an increase of S_2 ; this determine that the discharge flow from the tank1 in tank2 to be of the form:

$$\Delta F_2 = C\sqrt{L_{10}}(\Delta S_{2n} + \Delta S_{2d}) \quad (11)$$

Where ΔS_{2n} is the value of the section under normal functioning conditions and ΔS_{2d} is equivalent value of the section, caused by the fault.

Under these circumstances, by introducing the faults specified in equations (6) and (7), replacing $\Delta U_C = \Delta U_{Cn} + \Delta U_d$ and $\Delta S_2 = \Delta S_{2n} + \Delta S_{2d}$ we obtain:

$$\Delta \dot{x}_1 = -\frac{CS_{20}}{2A_1\sqrt{L_{10}}}\Delta x_1 + \frac{k_p}{A_1}(\Delta U_C + \Delta U_d) - \frac{C\sqrt{L_{10}}}{A_1}(\Delta S_{2n} + \Delta S_{2d}) \quad (12)$$

$$\Delta \dot{x}_2 = \frac{CS_{20}}{2A_2\sqrt{L_{10}}}\Delta x_1 - \frac{k_p}{A_2}(\Delta U_C + \Delta U_d) + \frac{C\sqrt{L_{10}}}{A_2}(\Delta S_{2n} + \Delta S_{2d}) \quad (13)$$

In equations (12) and (13) we have applied Laplace transform under zero initial conditions and using the transformations and the notes from the equations (8) and (9) it follows the operational form of the real process equations in which faults have been included.

Following the same steps to equations (12) and (13) as the relations (6) and (7) it results:

$$x_{1r}(s) = \frac{1}{Ts+1} \left[\frac{2x_{10}k_p}{F_{20}}\Delta U_{Cn}(s) + \frac{2x_{10}k_p}{F_{20}}\Delta U_d(s) - 2x_{10}\frac{\Delta S_{2n}(s)}{S_{20}} - 2x_{10}\frac{\Delta S_{2d}(s)}{S_{20}} \right] \quad (14)$$

$$x_{2r}(s) = \frac{A_1/A_2}{Ts+1} \left[-\frac{2x_{10}k_p}{F_{20}} \Delta U_{Cn}(s) - \frac{2x_{1r}k_p}{F_{20}} \Delta U_d(s) + 2x_{10} \frac{\Delta S_{2n}(s)}{S_{20}} + 2x_{10} \frac{\Delta S_{2d}(s)}{S_{20}} \right] \quad (15)$$

Where: $\frac{CS_{20}}{2A_1\sqrt{L_{10}}} = \frac{1}{T}$

From equations (8) and (9) it follows the process pattern, considered faultless $\Delta S_2 = 0$:

$$x_{1m}(s) = \frac{1}{Ts+1} \left[\frac{2x_{10}k_p}{F_{20}} \Delta U_{Cn}(s) - 2x_{10} \frac{\Delta S_{2n}(s)}{S_{20}} \right] \quad (16)$$

$$x_{2m}(s) = \frac{1}{Ts+1} \left[-\frac{2x_{10}k_p}{F_{20}} \Delta U_{Cn}(s) + 2x_{10} \frac{\Delta S_{2n}(s)}{S_{20}} \right] \quad (17)$$

We define the residues $r_1(s)$ and $r_2(s)$ [7]:

$$r_1(s) = x_{1r}(s) - x_{1m}(s) = \frac{1}{(Ts+1)} \frac{2x_{10}k_p}{F_{20}} U_d(s) - \frac{1}{(Ts+1)} 2x_{10} \frac{\Delta S_{2d}(s)}{S_{20}} \quad (18)$$

$$r_2(s) = x_{2r}(s) - x_{2m}(s) = -\frac{1}{Ts+1} \frac{2x_{10}k_p}{F_{20}} \Delta U_d(s) + \frac{1}{Ts+1} 2x_{10} \frac{\Delta S_{2d}(s)}{S_{20}(s)} \quad (19)$$

From the equations (18) and (19) it can be seen that the residues r_1 and r_2 are both of influenced by the faults ΔS_{2d} and ΔU_d .

In Figure 2, the upper part is represented by the level control structure of the real process. This control structure allows adjusting the output of the process to the prescribed value even when the occurrence of a fault (the control system succeeds to compensate the fault). The command value of the model plant is function of the command value of the real controller and the output from the residual generator block, so in fault condition, the outputs of the model will show the real value of the level, when changing the command received from the controller. The output of the real plant L_{1r} and L_{2r} are compared to the output of the model plant L_{1m} and L_{2m} and the difference represents the input in the residual generator block. By simply monitoring of the residues it is possible to predict the change in behaviour of the system from normal condition.

Using the simulation scheme presented in Figure 2, the following experimental results have been obtained. In Figure 3 we can observe the process and the model outputs in normal conditions. In this case the residuals r_1 and r_2 are "0" as is shows in Figure 4.

In Figure 5 and Figure 6 are represented the level for the model, respective the level for the real plant in fault condition, is considered the permanent fault $\Delta U_d = -0.2$ appeared at time $t = 40$ s. The residuals r_1 and r_2 , represented in Figure 7 respective Figure 8, indicate the occurrence of the fault.

Figure 2: Fault detection and level control structure

Figure 3: Process and model outputs in normal conditions

Figure 4: Residues in normal conditions

Figure 5: Level L_{1m} and L_{2m} for $\Delta U_d = -0.2$

Figure 6: Level L_{1r} and L_{2r} for $\Delta U_d = -0.2$

Figure 7: Residue r_1 for permanent fault $\Delta U_d = -0.2$

Figure 8: Residue r_2 for permanent fault $\Delta U_d = -0.2$

We consider that the fault $\Delta U_d = -0.2$ appears on the time $t = 40 \div 70$ s, in this case the level for the model is represented in Figure 9 and the level for the real plant is shown in Figure 10. Using the fault detection structure, the residues represented in Figure 11 and Figure 12 indicates the occurrence of the fault.

Figure 9: Level L_{1m} and L_{2m}

Figure 10: Level L_{1r} and L_{2r}

Figure 11: Residue r_1 for $\Delta U_d = -0.2$

Figure 12: Residue r_2 for $\Delta U_d = -0.2$

Figure 13: Level L_{1m} and L_{2mr} for $\Delta S_{2d} = 0.1$

Figure 14: Level L_{1r} and L_{2r} for $\Delta S_{2d} = 0.1$

Figure 15: Residue r_1 for $\Delta S_{2d} = 0.1$

Figure 16: Residue r_2 for $\Delta S_{2d} = 0.1$

In Figure 13 and Figure 14 are represented the level for the model, respective the level for the real plant in fault condition, is considered the permanent fault $\Delta S_{2d} = 0.1$ appeared at time $t = 60$ s. The residues represented in Figure 15 and Figure 16 indicates the occurrence of the fault.

5. Conclusions

In this paper a method for faults detection and localization using residual vectors was presented; the proposed method was theoretically developed and experimentally verified. It allowed detection and localization of two faults created in a real plant, including the detection of the cases when the control system succeeds to compensate the fault. This structure does not require supplementary equipments; it can be implemented as software complementary system on the existing monitoring digital control system from power plants. A series of case studies was realized regarding the possibilities for detection of the faults using residuals generator for the system. With the fault detection and localization scheme presented in this paper it can be detected the faults ΔU_d and ΔS_{2d} .

Acknowledgment

This work was supported by the strategic grant POSDRU/159/1.5/S/133255, Project ID 133255 (2014), co-financed by the European Social Fund within the Sectorial Operational Program Human Resources Development 2007 - 2013.

6. References

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