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Advanced Control System Development on the Basis of Festo Training Laboratory "Compact Workstation"

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Abstract: This article describes the development of automatic control system on the basis of Festo "Compact Workstation" training stand. Such control systems are used in different branches of industry and infrastructure including oil industry, chemical industry, water treatment, canalization and others. The stand allows realizing level, flow, pressure and temperature control systems, using pump, valves, discrete and analog sensors. Level control system is described in this work. PID (proportional integral derivative) controllers are used in these systems. Control is switched on and off and the parameters of control systems are changed by means of SCADA (supervisory control and data acquisition) system. During real technological processes, these actions are performed by the operator. The algorithm of the control system is realized using PLC (programmable logic controller). At the end of the article conclusions about the research are drawn.

Key words: PLC, SCADA, PID controller, liquid level control.

1. Introduction

Automatic control systems are used in different technological processes. Such systems control process parameters and ensure its stability according to technological conditions and users' demands. They prevent equipment used in the process from breakdown and reduce expenses for electricity and process maintenance. Regulation systems are often used in branches of industry connected with liquids, for example, oil and chemical water supply and canalization. Different parameters are controlled for different liquids, but the most common is level, flow, pressure and temperature control.

In this work automatic control for liquid level is developed on the basis of PID (proportional integral derivative) controller and methods for its optimization are offered.

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2. Problem Formulation

The provided solutions [1-3] for Festo "Compact Workstation" are based only on PID control are not flexible. The aim of this work is to develop more flexible and easy-to-use control methods for automatic control system for liquid level in reservoir. In order to achieve this aim, such four tasks are proposed:

(1) level regulation realization using PID regulator;

(2) control system optimization to reach its stability and suitable transition process;

(3) experiment using available equipment and software;

(4) conclusions about the results of the work.

3. Mathematical Model of Task Solution

Level regulation system is a closed-loop control system. Its output value x_0 is liquid level in the tank and controlled object is the pump together with the water tank. The rotational speed of the pump (or the corresponding voltage) is transferred to the liquid level. Here, the controlled object is regarded as the first order aperiodic block with a transfer function according to Eq. (1) [4].

$$W_{ob}(s) = \frac{k_{ob}}{1 + T_{ob}s} \qquad (1)$$

where, k_{ob} is the proportionality constant of the pump and T_{ob} is its time constant.

The proportionality constant of PID controller is applied to its proportional, integral and derivative parts. The algebraic transfer function of the system is Eq. (2) [4].

$$\Phi_{RS}(s) = \frac{W_R(s) \cdot W_{ob}(s)}{1 + W_R(s) \cdot W_f(s) \cdot W_{ob}(s)} \qquad (2)$$

where, $W_R(s)$ is the transfer function of the PID controller, $W_f(s) = k_f = 1$ is the transfer function of the feedback. The feedback only inverts the output value of the system (level). That is why its proportionality constant $k_{as} = 1$. The flowchart of level control system is shown in Fig. 1. x_{out} is level real value, σ_{xr} is the difference between level setpoint and real value (system error).

After the flowchart equations for level control system transfer function with P (proportional), PI (proportional integral), PD (proportional derivative) and PID controller are given.

The transfer function of the level control system with a P controller is Eq. (3).

$$\Phi_{RS}(s) = \frac{k_p \cdot k_{ob}}{(1 + T_{ob}s) \cdot (1 + k_p \cdot \frac{k_{ob}}{1 + T_{ob}s})} = \frac{k_p \cdot k_{ob}}{1 + T_{ob}s + k_p \cdot k_{ob}} \qquad (3)$$

The transfer function of the level control system with a PI controller is Eq. (4).

$$\Phi_{RS}(s) = \frac{k_p(T_i s + 1) \cdot k_{ob}}{(T_i s + T_i T_{ob} s^2) \cdot (1 + k_p(T_i s + 1) \cdot \frac{k_{ob}}{T_i s + T_i T_{ob} s^2})} = \frac{k_p \cdot k_{ob}}{T_i T_{ob} s^2 + (k_p k_{ob} + 1) T_i s + k_p \cdot k_{ob}} \qquad (4)$$

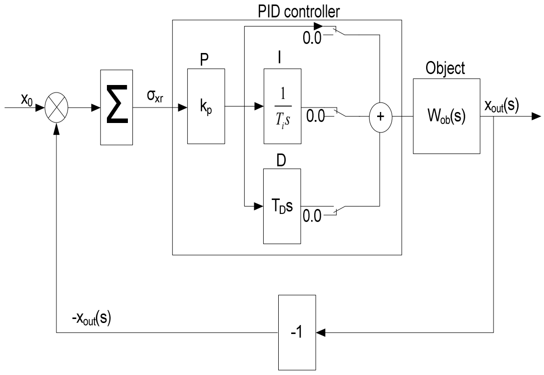

Fig. 1 Control system flowchart.

The transfer function of the level control system with a PD controller is Eq. (5).

$$\Phi_{RS}(s) = \frac{k_p(T_D s + 1) \cdot k_{ob}}{(1 + T_{ob}s) \cdot (1 + k_p(T_D s + 1) \cdot \frac{k_{ob}}{1 + T_{ob}s})} = \frac{k_p \cdot k_{ob}}{(T_{ob} + k_p k_{ob} T_D)s + k_p k_{ob} + 1} \qquad (5)$$

The transfer function of the open-loop of level control system with PID controller is given in Eq. (6), and the transfer function of level control system is given in Eq. (7).

$$W_v(s) = W_R(s) \cdot W_{ob}(s) = \frac{k_p k_{ob} \cdot (T_D T_i s^2 + T_i s + 1)}{T_i s + T_i T_{ob} s^2} \qquad (6)$$

$$\Phi_{RS}(s) = \frac{k_p k_{ob} \cdot (T_D T_i s^2 + T_i s + 1)}{(T_i s + T_i T_{ob} s^2) \cdot (1 + k_p k_{ob} \cdot \frac{(T_D T_i s^2 + T_i s + 1)}{T_i s + T_i T_{ob} s^2})} = \frac{k_p k_{ob} \cdot (T_D T_i s^2 + T_i s + 1)}{(T_{pmp} + k_p k_{ob} T_D) \cdot T_i s^2 + (1 + k_p k_{ob}) \cdot T_i s + k_p k_{ob}} \qquad (7)$$

The characteristic equation of the level control system is the denominator of the transfer function equal to zero.

Skopis [5] shows that $k_{ob} = 2.43$, $T_{ob} = 118$ sec.

The transfer function of the controlled object taking into consideration these constants is Eq. (8).

$$W_{ob} = \frac{2.43}{1 + 118s} \qquad (8)$$

After describing transfer function of level control system, a suitable method of the optimization of the system is chosen. There are different methods to find optimal parameters of the regulator, for example, the good gain method or Ziegler-Nicols' method [4].

The good gain method is an experimental method. It can be used either for a physical process or for a process simulator if the mathematical model of the process is known. It is used to get acceptable stability of the controlled process (good stability, but not too good as it gives too slow response). To see if the stability of the process is acceptable, a positive step change of the setpoint should be made. Stability is acceptable if the undershoot after the first overshoot of the response signal is small or barely observable. The minimum gain value for P controller for system with acceptable stability can be called K_{pGG}, time between the overshoot and the undershoot of the step response is called T_{ou}. The optimal coefficients for PI controller are found from Eqs. (9) and (10) [6].

$$K_p = 0.8K_{pGG} \tag{9}$$

$$T_i = 1.5T_{ou} \tag{10}$$

If not PI but PID controller is used in the control system, T_D is defined by Eq. (11) [6]:

$$T_D = \frac{T_i}{4} \tag{11}$$

which is the relation between T_D and T_i that used in Ziegler-Nicols' method. This method is described below [6].

Ziegler-Nicols' method starts from increasing gain value of the proportional control system till large oscillations of the output parameter begin, such limit value of the gain is called K_{pm}. Also the oscillation period—T_{os} is taken into consideration. For PI control system coefficients offered by Ziegler-Nicols' method are defined by Eqs. (12) and (13) [4].

$$k_p = \frac{k_{pm}}{2.2} \tag{12}$$

$$T_i = \frac{T_{sv}}{(0.7...1.2)} \tag{13}$$

PID controller optimal parameters according to this method are defined by Eqs. (14)-(16) [4]:

$$k_p = \frac{k_{pm}}{1.6} \tag{14}$$

$$T_i = \frac{T_{sv}}{(1.5...2)} \tag{15}$$

$$T_D = \frac{T_{sv}}{8} \tag{16}$$

In this paper, the optimal parameters of the regulator are found according to Skogestad method. This method is not so widespread in literature as Ziegler-Nicols' method and is comparatively new. That is why its usage for optimization of PID controller's parameters is innovation. Using this method, a new deeper research can be made. In this case, this method can be described as Eq. (17) [6].

$$W_{proc}(s) = W_{ob}(s) = \frac{2.43}{1+118s},\ T_D = 0 \tag{17}$$

where, $W_{proc}(s)$ is the transfer function of the process. Proportionality coefficient and integration time constant are chosen from Eqs. (18) and (19) [6]:

$$k_p = \frac{118}{2.43 \times T_C} \tag{18}$$

$$T_i = \min(118, cT_C) \tag{19}$$

It is assumed that $c = 4$. T_C can be chosen randomly [6].

To evaluate control system stability Routh criterion is used in this works. It takes into account the coefficients of the characteristic equation. As an example, control system with PI controller is regarded here.

The characteristic equation of this control system is Eq. (20):

$$118T_i s^2 + (2.43k_p + 1)T_i s + 2.43k_p = 0 \tag{20}$$

The Routh table for such system is Table 1. All the coefficients in its left column must be positive if system is stable [4].

The artificial c_1 is calculated from Eq. (21).

$$c_1 = \frac{a_1 \cdot a_0 - a_2 \cdot 0}{a_1} = a_0 \tag{21}$$

As can be seen from Table 1, as the proportionality

Table 1 Routh table for level control system with PI controller.

$a_2 = 118T_i$	$a_0 = 2.43k_p$	0
$a_1 = (2.43k_p+1)\cdot T_i$	0	0
$c_1 = 2.43k_p$	0	0

constant k_p is positive, control system with PI controller is stable with any values of regulator coefficients. The same research on mathematical models of systems with P, PD and PID controllers has the same results.

4. Experiment

Festo Compact Workstation stand is used for the experiment. It is shown in Fig. 2.

The scheme of level control system is shown in Fig. 3.

This system regulates liquid level in B102 tank. Water is pumped to it from B101 tank by P101 pump through V101 manual valve. Liquid level in the tank is controlled by an ultrasonic sensor [7, 8] which is situated on LIC 102 position. The sensor takes level actual value which should stay constant even if disturbance is applied to the control system. Ball valve V102 can be closed or opened to make disturbance [1].

Compact Workstation is driven by PLC, the overall PLC algorithm block scheme is shown in Fig. 4. Then the steps of the algorithm are described.

Step 1: Enable handling of analog input signal from level sensor in B102 water tank. Transform signal value from PLC units to millimeters and specify signal limits, enable the analog output driving pump P10.

Step 2: if discrete Start signal (S1) is active (state "1") and discrete Stop signal is not active (state "0") then enable control system—put discrete signal "System_Enable" active. Go to step 4;

else

go to step 3.

Step 3: If Stop signal is active then control system is disabled.

If stop signal is active then control system is disabled,

else

do nothing.

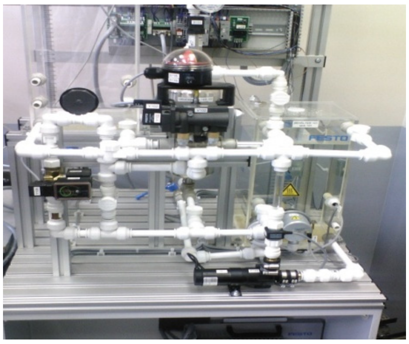

Fig. 2 Compact Workstation outlook.

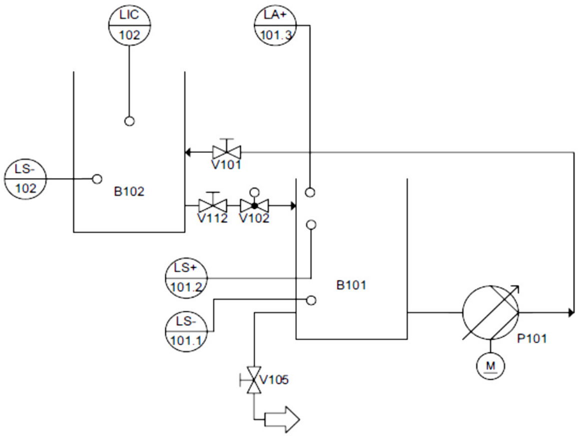

Fig. 3 Level control system scheme [3].

Step 4: If control system is enabled then reset Start signal,

else

disable level control (reset "Level_Ctrl_Enable" bit), reset Stop signal, go to END.

Step 5: If level control is enabled ("Level_Ctrl_Enable" bit is set) then control water level in B102 tank by regulating analog output singnal on P101 pump with the help of PID controller,

else

go to end.

Start, stop and "Level_Ctrl_Enable" signals are set by pressing buttons on SCADA. Separate signals for enabling the whole control system and level control because it is also considered to control flow, pressure and temperature of water.

Optimal values of the PI controller coefficients are found by Skogestad method which was described in Section 3.

The curves of transition process of this control

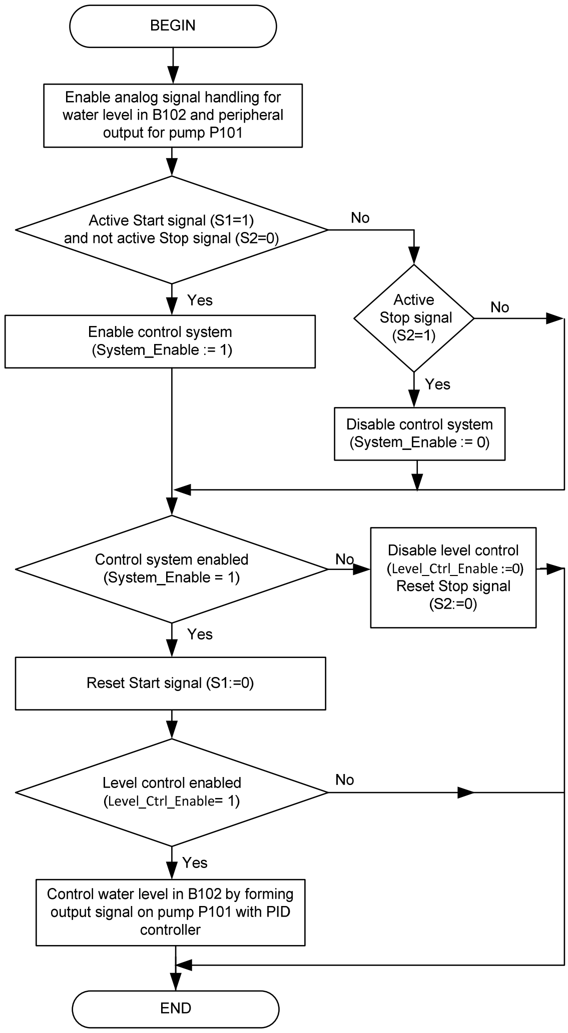

Fig. 4 Main PLC algorithm block scheme

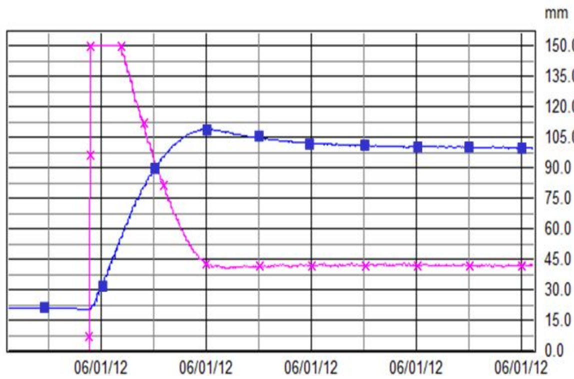

Fig. 5 Level control system with PI controller transition process curves. (k_p = 4.85 and T_i = 40 s, level setpoint is 100 mm).

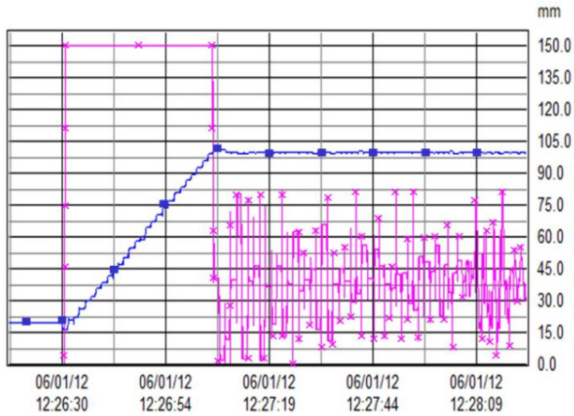

Fig. 6 Level control system with PI controller transition process curves (k_p = 96.99 and T_i = 2 s, level setpoint is 100 mm).

system (with different k_p and T_i) are shown in Figs. 5 and 6. The curve with squares everywhere is liquid level actual value, the curve with crosses is the rotational speed of the pump motor.

The curves of level control system transition process with k_p = 4.85 and T_i = 40 sec (T_C = 10 sec) are shown in Fig. 5. With such coefficients overshoot is about 10% that is allowed in such processes. Oscillations attenuate, after the first maximum of the level curve. Control time is about 80 s. The pump 15 s works with a maximum speed, then the speed gradually decreases and becomes equal to value that corresponding to level setpoint.

Reducing T_C to 0.5 s, k_p = 96.99, T_i = 2 s (Fig. 6), control time slightly and there is almost no overshoot with such parameters. However, the speed curve has oscillations with amplitude about half a maximum and the value of the speed can drop even to zero.

The results of the experiment show that the rise of PI controller proportionality coefficient influences the oscillations of pump motor speed that is harmful for the pump. It should be taken into consideration while improving transition process of the system.

To simplify the research for this paper, the pump was considered to be as the first order aperiodic block, and, according to the Routh algorithm the control system should be stable with any PI controller parameters. However, the results of the experiment show that the system could become unstable with the certain k_p parameters. The cause of it could be that the controlled object is actually the second order aperiodic block, with a transfer function according to Eq. (22) [4].

$$W_{ob}(s) = \frac{k_{ob}}{T_{ob2}s^2 + T_{ob1}s + 1} \quad (22)$$

where, k_{ob} is the proportionality constant of the pump and T_{ob1} and T_{ob2} are its time constants.

So, the transfer function of the level control system with a PI controller changes to Eq. (23).

$$\Phi_{RS}(s) = \frac{k_p(T_i s + 1)\cdot k_{ob}}{T_i T_{ob2}s^3 + T_i T_{ob1}s^2 + (k_p k_{ob} + 1)T_i s + k_p k_{ob}} \quad (23)$$

The characteristic equation for this control system is Eq. (24).

$$T_i T_{ob2}s^3 + T_i T_{ob1}s^2 + (k_p k_{ob} + 1)T_i s + k_p k_{ob} = 0 \quad (24)$$

The Routh table for this system is in Table 2.

The artificial c_0 of the Routh table for such system is calculated from Eq. (25).

$$c_0 = \frac{a_2 \cdot a_1 - a_3 \cdot a_0}{a_2} = T_i + T_i k_{pmp} k_p - \frac{T_{pmp2} \times k_{pmp} k_p}{T_{pmp1}} \quad (25)$$

The artificial c_0 must be positive for the stability of the system. As can be seen from Eq. (19), c_0 can be negative with large k_p and small T_i that could lead to the instability of the system.

Apart from optimal PID/PI controller coefficients selection another simple method for level control system transition process improvement is offered in this paper. This method can be used with random regulator parameters.

It is clearly seen from Figs. 5 and 6 that the pump works with maximum speed for some time. The speed starts decreasing after certain value of liquid level in the tank before reaching steady-state level value.

So, one more experiment was made within this work. Firstly, the pump is driven with the maximum speed putting control voltage 10 V to the pump control analog input. After reaching a certain level value (here 90% of level setpoint) PID controller is connected to pump control analog input. If the speed of the pump motor is not sufficient, level can decrease below 90% of setpoint. So, initial value is connected to the integral part of PID controller in order to prevent such situation. This initial value should be greater than the speed necessary to reach setpoint. When liquid level in the tank reaches greater value (here, 95% of the setpoint), initial value is disconnected from the integrator. Without disconnecting it, level would be greater than setpoint.

Table 2 Routh table for level control system with PI controller (pump is the second order aperiodic block).

$a_3 = T_{ob2}T_i$	$a_1 = (k_{ob}k_p+1)T_i$	0
$a_2 = T_{ob1}\cdot T_i$	$a_0 = k_{ob}k_p$	0
$c_0 = T_i + T_i k_{ob} k_p - \frac{T_{ob2}\cdot k_{ob} k_p}{T_{ob1}}$	0	0

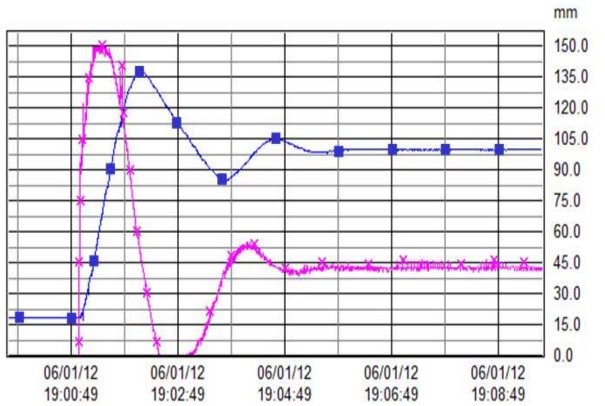

Fig. 7 Level control system with PID controller transition process curves (k_p = 2, T_i = 10 s, T_D = 10 s, level setpoint is 100 mm).

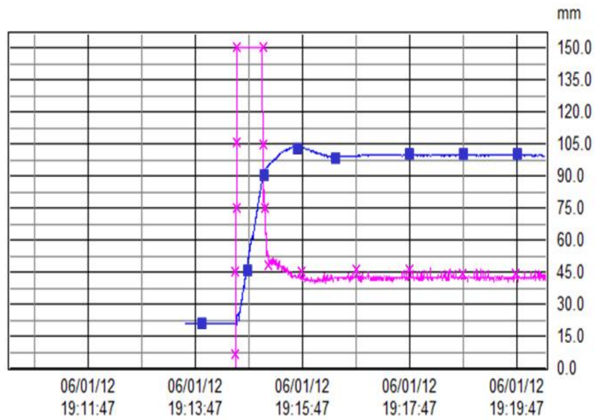

Fig. 8 Level control system with “stepped” controller transition process curves (k_p = 2, T_i = 10 s, T_D = 10 s, level setpoint is 100 mm).

Level control system transition curves with “pure” PID controller and “stepped” controller offered in the experiment are shown in Figs. 7 and 8, respectively.

The trends show that usage of “stepped” controller considerably reduces overshoot—from 40% to less than 5%. Control time also decreases. Level oscillations attenuate after the first maximum. Comparing how the pump works with "pure" PID and "stepped" controller, it is seen that the pump completely switches of in case of PID controller and it does not switch off with "stepped" controller. As a whole usage of "stepped" controller with random coefficients allows reaching level control system transition process that is close to optimization.

5. Conclusions

Using Skogestad method for optimization of level control system with PID controller the system is stable and its transition process is acceptable (overshoot does not exceed 10%, no steady-state error).

With larger k_p and smaller T_i regulation time and controlled parameter overshoot decrease. With lager T_i and smaller k_p manipulated value (pump motor speed of level control system) changes gradually without jump. Gradual change of manipulated value prevents its oscillations and the whole system stays stable.

Large value of proportionality coefficient leads to large manipulated value (here pump motor speed) oscillations. If control system response on manipulated value were faster, it could lead to system instability.

Using PLC, a so-called "stepped" control method was implemented be implemented to improve control system transition process. With the help of this algorithm the overshoot decreased from 40% to less than 5%, as well control time decreased without searching optimal values for PID controller coefficients.

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