Management of the objects with a negative self-regulation

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Abstract. The article considers methodical issues of sustainable management of objects with negative self-regulation using both conventional methods and original approaches, consisting in the application of two functions additional to PID-control. The first control function is associated with the binding of the controlled variable in a predetermined range, while the second one is related to correction of this variable to achieve the required control precision. The methods of mathematical modeling of control processes in closed systems serve to test the effectiveness of the proposed additional control functions. Author proposes correlations for optimal tuning of PID-controller in the management of the object with a negative self-regulation with and without application of the additional control functions. It is shown that, when using additional functions, management quality of the object with a negative self-regulation is not inferior to that of the objects with a positive self-regulation, when using conventional methods.

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Introduction

Description of the objects properties with a negative self-regulation as the objects, unsustainable in terms of their management, is given, for example, in [1, 2, 3, 4]. However, these works lack data on the methods of sustainable management of these objects and ensuring the high management quality of their output parameters. It is noted in [5] that the objects with a negative self-control are quite widespread in industry.

Main part

The differential equation, describing the behavior of the controlled object with a negative self-control, has the form:

$$T_O \frac{dY(t)}{dt} - Y(t) = K_O X(t - t_O), \qquad (1)$$

where $Y(t)$ is the increment of the controlled variable; $X(t - t_O)$ is the increment of the controlling action, delayed in time by the lag factor t_O; K_O is object transition factor; T_O is time constant.

In addition to equation (1), the behavior of some objects with a negative self-regulation, which include the objects with controlled temperature as a variable, related to the exothermic processes, are described by the equation [6, 7, 8, 9]:

$$-T_O \frac{dY(t)}{dt} + Y(t) = K_O X(t - t_O) \qquad (2)$$

Simulation of a negative self-controlled object system operation, described by equation (2), has shown that the sustainable operation of the control system can be achieved using a PID-controller with the settings defined within fairly narrow ranges. Configuration of the optimal settings of PID-controller depending on object parameters with self-control, in terms of achieving the minimal transition time, is proposed in [10]. According to this work, the optimal settings are proportional to ratio between a time constant T_O and the product of the transition factor K_O and object lag factor t_O. In this paper, the optimal settings of PID-controller were found for a number of objects with a negative self-control. This was done based on the minimum value of the integral quadratic criterion of the management quality. Also, the values of the proportionality coefficients, providing relation between the optimal setting of PID-controller parameters and the ratio of the controlled object parameters, were found. Equations to determine the optimal settings of PID-controller in the management process of the object with a negative self-control are listed below:

$$KP = 0{,}6 \cdot \frac{T_O}{K_O t_O}; \qquad (3)$$

$$K_I = 0{,}05 \cdot \frac{T_O}{K_O t_O}; \qquad (4)$$

$$K_D = 2{,}0 \cdot \frac{T_O}{K_O t_O}; \qquad (5)$$

where K_P, K_I, K_D are gains of proportional, integral and differential components of controlling action of PID-controller, respectively. As was shown by the conducted search, for optimal settings of PID-controller, the presence of the integral term in the controlling action during the management of an object with a negative self-control degrades the management quality (increases the value of the integral quadratic criterion), though its relatively small value, in accordance with equation (4), allows one to eliminate static error in process variable controlling.

Optimal settings of PID-controller, found using equations (3), (4) and (5), provide its sustainable operation, though the management quality of process variable is low, since the damping of oscillations of the controlled variable is relatively slow. Besides, small changes in the parameters of the controlled object disrupt the sustainability of the regulator operation due to process transient effects, and thus require its corrective adjustment. To overcome these drawbacks of the system providing management of the object with negative self-regulation, we propose to expand system functions by fixing the value of process variable at a given level in addition to its PID-control. This can be done by setting the controlling action, at which $\frac{dY(t)}{dt}=0$ when concerned controlled variable appears within a given region:

$$\left|P(t)-P_{PR}\right|<\varepsilon, \qquad (6)$$

where ε is tolerated error of process parameter control; P is the value of the parameter; and R_{PR} is prescribed value of the parameter.

If the behavior of the controlled object is described by equation (1), then the condition $\frac{dY(t)}{dt}=0$ corresponds to the formation of the controlling action according to the equation:

$$X(t-t_O)=-\frac{Y(t)}{K_O} \qquad (7)$$

If the behavior of the controlled object is described by equation (2), then the condition $\frac{dY(t)}{dt}=0$ corresponds to the formation of the controlling action according to the equation:

$$X(t-t_O)=\frac{Y(t)}{K_O} \qquad (8)$$

Equations (7) or (8) are used to implement additional control function, providing the fixation of the controlled variable at a predetermined level. If during the implementation of fixation function of the controlled variable the value of the process variable leaves the specified area under the influence of disturbances, i.e. in case of violation of the condition (6), operation of PID-controller is resumed (controlling action is determined by the PID-law). When controlled parameter gets into a given range, its value is fixed again.

When using described additional function of control system, optimal settings of PID-controller, defined by equations (3), (4) and (5), should be refined. When employing the additional functions for fixation of controlled variable at a given level, the proportionality coefficients in equations, determining the optimal settings of PID-controller, are refined based on simulation of the transient processes, associated with the management of the objects with a negative self-regulation, by the minimum value of the integral quadratic criterion of management quality:

$$K_p=0{,}959\cdot\frac{T_O}{K_O t_O}; \qquad (9)$$

$$K_i=0{,}0639\cdot\frac{T_O}{K_O t_O}; \qquad (10)$$

$$K_D=2{,}5\cdot\frac{T_O}{K_O t_O} \qquad (11)$$

To illustrate the advantages of using the PID-control with the additional function to fix the controlled parameter at a given level in the management of an object with a negative self-regulation, author performed simulation of operation of the two control systems for one and the same object: using only the PID-controller and employing the PID-controller with the additional option of fixing the process variable at a predetermined level. Since the object in question is non-stationary with variable parameters, the transition factor of the object in the simulation was changed in order to determine the boundaries of the sustainable operation of regulators without changing their initial settings. Thus, here a semi-batch reactor temperature control was simulated for the exothermic stage of polyvinyl alcohol acetylation. In this case the reactor was an object with a negative self-regulation. Average values of the controlled object parameters were as follows: K_O=80°C; T_O=50 s; t_O = 20 s; controlling action was determined as the degree of the control valve opening (dimensionless value).

Optimal settings for the control system, consisting of only a PID-controller, were determined by the equations (3), (4) and (5), whereas for the control system with a PID-controller and an additional fixation function of the controlled parameter at a predetermined level was determined by equations (9), (10) and (11) for the mean values of the controlled object parameters. To determine the sustainable operation regions of the control systems, the value of the transition factor of the controlled object was varied from its average value both upward and downward without changing the settings of PID-controller. Simulation data on control systems operation are shown in Tables 1 and 2.

Table 1. Sustainable operation region of temperature PID-controller without additional control functions.

Transition factor, K_O, deg	Integral quadratic criterion, deg^2s.	Duration of the transient process, s.	Sustainability of object management with a negative self-regulation
70	-	-	Unsustainable
75	23842	710	Sustainable
80	21982	540	Sustainable
90	22246	650	Sustainable
100	-	-	Unsustainable

Table 2. Sustainable operation region of temperature PID-controller with additional function to fix controlled variable at a predetermined level.

Transition factor, K_O, deg	Integral quadratic criterion, deg^2s.	Duration of the transient process, s.	Sustainability of object management with a negative self-regulation
10	12723	70	Sustainable
20	941	50	Sustainable
40	738	40	Sustainable
50	691	40	Sustainable
60	660	40	Sustainable
80	631	40	Sustainable
90	2709	110	Sustainable
100	2657	100	Sustainable
102	2710	100	Sustainable
103	2736	100	Sustainable
104	2763	100	Sustainable
105	-	-	Unsustainable

As is obvious from the simulation results of control systems with a negative self-regulation, shown in Tables 1 and 2, the transfer coefficient of the controlled object Co=80°C corresponds to the minimum value of the integral quadratic criterion that is due to the fact that this value is the average for the object, for which the optimal settings of temperature PID-controller were found according to the equations (3), (4) and (5) or equations (9), (10) and (11). The region of sustainable operation of temperature PID-controller without additional fixation function of the controlled variable is relatively narrow and varies from K_O=75°C to K_O=90°C, while the sustainable operation region for temperature PID-controller with an additional fixation function of the controlled variable is much wider and changes from K_O=10°C to K_O=104°C for one and the same management object. The values of the integral quadratic control quality criterion, in the case of availability of an additional function to fix the controlled variable at a given level, are an order of magnitude lower than those for the case when this function is not available.

It should be noted that Tables 1 and 2 show the simulation results of control systems of the object having relatively large lag factor t_O=20 s with a time constant T_O = 50 s. For controlled objects with less lag factor, sustainable operation region of temperature PID-controller with an additional function of fixation of the controlled variable at a given level is much broader than the one presented in Table 2. We consider a semi-batch reactor as an object under study, in which an exothermic reaction for producing styrene-acrylic dispersion is taking place. The object with a negative self-regulation has following average parameters: K_O=64°C; T_O=110 s; and t_O = 3 s. For the management system of this object we define boundaries of sustainable operation region for temperature PID-controller. The results on defining sustainable operation region for control system of concerned object are presented in Table 3. These data indicate that virtually at any variations of controlled object's transition factor, associated with the unsustainability of the process under control at a relatively small delay of the object, the use of PID-controller with the additional option of fixing the controlled variable ensures sustainable management of the object with a negative self-regulation without changing the settings of the controller. For objects with a negative self-regulation and a small lag factor, relation of optimal settings of PID-controller in case of availability of an additional fixation function for the controlled variable to the controlled object parameters is not so significant due to the large range of variation of the object's transition factor changing from K_O=10°C to K_O=1000°C and affecting the accuracy of regulation and integral quadratic criterion. Therefore, the minimum value of the integral quadratic criterion does not apply to the average value of the transition factor K_O=64°C; its value mainly decreases with increasing transition factor of the controlled object.

Table 3. Sustainable operation region for temperature PID-controller with additional fixation function of a variable with respect to an object with a negative self-regulation and a small lag factor.

Transition factor, K_O, deg	Integral quadratic criterion, $deg^2 s$.	Duration of the transient process, s.	Sustainability of the object management
10	951	42	Sustainable
30	521	21	Sustainable
50	387	15	Sustainable
64	338	12	Sustainable
80	277	12	Sustainable
100	224	9	Sustainable
120	201	9	Sustainable
140	142	12	Sustainable
200	88	9	Sustainable
300	79	9	Sustainable
400	253	9	Sustainable
500	181	6	Sustainable
1000	3455	81	Sustainable

Let illustrate the shape of the transient process, when using a temperature PID- controller with the additional fixation function of the controlled variable for the case, when transition factor K_O=64°C (Table 3). Transition process, associated with a change of temperature setting to controller from 75°C to 80°C, is shown in Fig. 1.

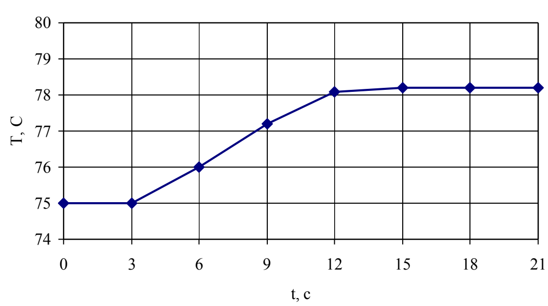

Fig. 1: The transition process at PID-regulation with additional fixation function of the process variable.

Duration of the transient process is 12 seconds providing the time constant is T_O =110 s and lag factor is t_O=3 s. The permissible error of temperature stabilization is ε=3°C. Fixation of the process variable at a given level consists in maintaining its constant value after entry into the specified area.

The width of the sustainable operation region for PID-controller operation with additional fixation function of the controlled variable is determined by the permissible error of control ε.

The increase in the permissible error extends the sustainable operation region for the control system. Therefore the choice of the permissible error of control must be carried out taking into account the desired width of the system's sustainable operation region and the required control accuracy of the process parameters. If a combination of both of these requirements cannot be achieved, it is possible to add a second additional correction function of the controlled variable to an additional fixation function of the controlled variable by changing the controlling action. The control algorithm in such correction includes the following steps: achieving by a PID-controller of allowable error ε of parameter control, execution of the correction of controlled variable and its fixation. Correction is made after the completion of the first phase by delivering to controlled object the maximum or minimum value of controlling action depending on the sign of the difference between the target and the current values of the controlled parameter.

The controlled parameter is monitored during the correction. When it reaches predetermined value with a higher accuracy, third control step is performed. It should be noted that the attainment of a higher accuracy during the correction comparing to that achieved at control process is possible due to its execution without feedback.

Figure 2 shows the same transient process as presented in Fig.1, except the fact that it was obtained at PID-control with an additional correction and fixation function of the process parameter.

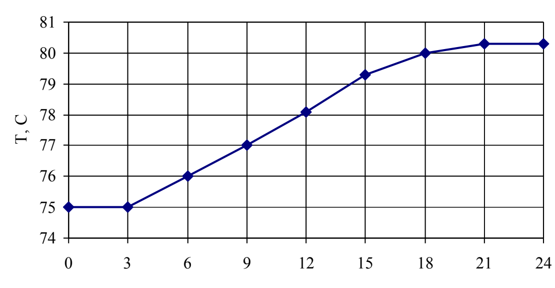

Fig. 2. The transition process at PID-control with an additional correction and fixation function of the process parameter.

Conclusion

Sufficiently high management quality of process parameter for the object with a negative self-regulation, conducted with the employment of the PID-controller, based on developed control algorithm with the additional correction function of the controlled variable and fixation of this variable, is provided within a wide range of variations of transition factor of the controlled object due to instability of the technology processes lacking the adjustment of the regulator.

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