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Compare of Transient Quality in Automatic Control Systems with Classic PID Algorithm and Optimal Regulator

G. T. Kulakov[1], **K. I. Artsiomenka**[1]

[1]Belarusian National Technical University (Minsk, Republic of Belarus)

Abstract. Currently, about 90–95% of generic controllers use the PID algorithm to generate control actions, while 64% of the PID controllers are used in single-circuit automatic control systems. Most of industries (power industry among them) use hundreds of automatic control systems. The quality of their work is the basis of economic efficiency of technical processes, ensuring safety, reliability, durability and environmental friendliness of both technological equipment and automation equipment. There are different modifications of PID-controller structure implementation. In practice the ideal PID controller with a filter and the classic PID regulator (serial connection of the ideal PI controller and the real PD regulator as the direct action elements) are widely used. The problem of choosing a rational structure and a method of parametric optimization of PID controllers, which provide the best direct indicatives of the quality in the development of the main effects in single-circuit automatic control systems, becomes urgent. However, only for the classical PID controllers, which are widely used at present, there are more than three hundred methods for adjusting the three parameters of the optimal dynamic adjustment, as well as the ballast time constant. This results in arising a problem of substantiation of the best structure and method of parametric optimization of classical PID regulators. As a basic option, one of the simplest and most obvious one, viz. the method of automated adjustment of the controller in the Simulink MatLab environment had been chosen, which was compared with the method of full compensation in general for objects with a transfer function in the form of an inertial link with a conditional delay. Two variants of control action realization on the basis of the structural scheme of the optimal regulator developed by the Belarusian national technical University were also offered. In contrast with the classic PID controller, the optimal controller has one parameter of dynamic adjustment setting. The results of simulation of transients at basic perturbations confirmed that the best direct indicatives of the quality are provided with an optimal regulator, which makes it possible to recommend it for wide implementation instead of the classic PID controllers.

Keywords: transfer function, transient process, classic PID controller, optimal regulator, directly indicative of the quality, single-circuit automatic control system

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Сравнение качества переходных процессов систем автоматического управления с классическим ПИД-алгоритмом и оптимальным регулятором

Г. Т. Кулаков[1], **К. И. Артёменко**[1]

[1]Белорусский национальный технический университет (г. Минск, Республика Беларусь)

Реферат. В настоящее время около 90–95 % типовых регуляторов используют ПИД-алгоритм формирования управляющих воздействий, при этом среди ПИД-регуляторов 64 %

Адрес для переписки	Address for correspondence
Кулаков Геннадий Тихонович Белорусский национальный технический университет просп. Независимости, 65/2, 220013, г. Минск, Республика Беларусь Тел.: +375 17 293-91-45 tes_bntu@tut.by	Kulakov Gennady T. Belarusian National Technical University 65/2 Nezavisimosty Ave., 220013, Minsk, Republic of Belarus Tel.: +375 17 293-91-45 tes_bntu@tut.by

используется в одноконтурных системах. Большинство отраслей промышленности, в том числе энергетика, содержат сотни систем автоматического управления, качество работы которых является основой экономической эффективности технических процессов, обеспечивая безопасность, надежность, долговечность и экологичность работы как технологического оборудования, так и самих технических средств автоматизации. Существуют разные модификации реализации структуры ПИД-регуляторов. На практике чаще всего применяют идеальные ПИД-регуляторы с фильтром, а также классические ПИД-регуляторы как последовательное соединение идеального и реального ПД-регуляторов в виде звеньев быстрого реагирования. Актуальной становится задача выбора рациональной структуры и метода параметрической оптимизации ПИД-регуляторов, которые обеспечивают лучшие прямые показатели качества при отработке основных воздействий в одноконтурных системах автоматического управления. Вместе с тем только для классических ПИД-регуляторов, широко используемых в настоящее время, существует более трехсот методов настройки трех параметров оптимальной динамической настройки, а также балластной постоянной времени. Из-за этого возникает проблема обоснования лучшей структуры и метода параметрической оптимизации классических ПИД-регуляторов. В качестве базового варианта выбран один из самых простых и наглядных – метод автоматизированной настройки регулятора в среде Simulink MatLab, который сравнивался с методом полной компенсации в общем виде для объектов с передаточной функцией в виде инерционного звена с условным запаздыванием. Также предложены два варианта реализации управляющего воздействия на базе структурной схемы оптимального регулятора, разработанного Белорусским национальным техническим университетом. В отличие от классического ПИД-регулятора оптимальный регулятор имеет один параметр динамической настройки. Результаты моделирования переходных процессов при основных возмущениях подтверждают, что лучшие прямые показатели качества обеспечивает оптимальный регулятор. Это позволяет рекомендовать его для широкого внедрения вместо классических ПИД-регуляторов.

Ключевые слова: передаточная функция, переходной процесс, классический ПИД-регулятор, оптимальный регулятор, прямые показатели качества, одноконтурная система автоматического управления

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Introduction

Adaptive control systems design is one of most effective method to upgrade regulation quality of process variables. Adaptive control systems must consider plant’s dynamic behaviours for wide range of load variation and dynamics of disturbances. They must use combined control principle in response to deviation and disturbance [1].

Long list of papers verifies this problem’s relevance and importance. These scientific papers deal with PID controllers’ adjustment and their realization [2–10]. This type of controller is the most difficult for adjustment among continuous controllers. PID controllers are used to regulate plants those are described differential equations of higher order. So transfer functions of plants can’t be approximated dynamic elements of first order with time delay, because they can’t give significant improvement of PID controller control quality [5]. Problem of adaptation automatic process regulator settings is reputed relevance too, because dynamic behaviours of plant are varied in wide range of load variation [6].

Within the order of 90–95 % under service regulators are using PID algorithm [6]. Also 64 % PID controllers are used in single loop automatic control systems and 36 % are used in multi loop systems. Thus problem of design and parametric optimization method for PID controllers becomes relevance. Solution to this problem lets to get best regulation costs in single loop automatic control systems to the different disturbances.

Description of simulation model

Block diagram of transient simulation for single loop automatic control system (ACS) is shown in the fig. 1.

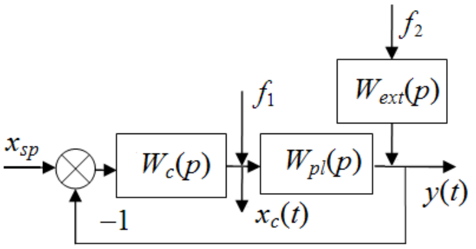

Fig. 1. Block diagram of transient simulation: x_{sp} – set point of controlled variable; $W_c(p)$ – controller's transfer function; $W_{pl}(p)$ – plant's transfer function; $W_{ext}(p)$ – transfer function of external disturbance; f_1 – internal disturbance; f_2 – external disturbance; $x_c(t)$ – control action; $y(t)$ – controlled variable

Plant's transfer function is a second-order relaxation circuit with delay time. Parameters of this transfer function are specified with the help of plant's transfer function experiment diagram for controlling action channel [9]

$$W_{pl}(p) = \frac{k e^{-\tau_c p}}{(Tp+1)(\sigma p+1)} = \frac{1{,}6 e^{-11{,}2p}}{(101p+1)(19p+1)}, \qquad (1)$$

where k – plant's transfer function coefficient; T, σ – larger and lesser transfer function time constants, s; τ_c – delay time for controlling action channel, s.

Plant's transfer function for external disturbance channel

$$W_{ext}(p) = \frac{k_{ext}}{T_{ext} p + 1} = \frac{10}{10p+1}, \qquad (2)$$

where k_{ext} – transfer function coefficient for external disturbance channel; T_{ext} – transfer function time constant for external disturbance channel, s.

Widely used transfer function of classic PID controller is written as

$$W_c(p) = \frac{k_c (T_i p + 1)(T_d p + 1)}{T_i p (T_b p + 1)}, \qquad (3)$$

where k_c – transfer function coefficient of controller; T_i, T_d, T_b – integration, derivative and ballast time constants, s.

There are a lot of different adjustment methods for PID controllers at this moment [2]. Automatized controller adjustment with the help of Simulink MatLab API is one of the most simplest methods. Process of adjustment and optimization is written [7]. Settings of optimal dynamic adjustment for PID controller after automatized controller adjustment are: k_c = 2,789, T_i = 0,0246 s, T_d = 38,67 s and T_b = 0,4 s (first variant). These settings are chosen of minimum integral of the squared error (ISE). Automatic control system has minimum overshoot and minimum time, when controlled variable get to the controller's dead band (±2 %), under the given settings. This method can't help to calculate controller settings, which let controlled variable be changed without overshoot to the controlled variable step input.

Full compensation method in general terms will be the second variant of PID controller dynamic adjustment settings [9]. Derivative time is equal to delay time for controlling action channel under this method. Ballast time constant is calculated as mean value $T_b = T_d/N$, where $N = 10$ [2]. Time constants are equal for the second variant of PID controller dynamic adjustment settings:

$$T_i = T + \sigma = 101 + 19 = 120 \text{ s}; \tag{4}$$

$$T_d = \tau_c = 11{,}2 \text{ s}; \tag{5}$$

$$T_b = T_d/N = 11{,}2/10 = 1{,}12 \text{ s}. \tag{6}$$

Transfer function coefficient is calculated as

$$k_c = \frac{T + \sigma}{4\xi^2 k \tau_c} = \frac{101 + 19}{4 \cdot 1^2 \cdot 1{,}6 \cdot 11{,}2} = 1{,}674, \tag{7}$$

where ξ – damping coefficient (equal 1), that help to rectify overshoot to the controlled variable step input.

PID controller structure can be made with the help of optimal regulator transfer function to the controlled variable step input [10]. Optimal regulator let to operate input step without overshoot (fig. 2).

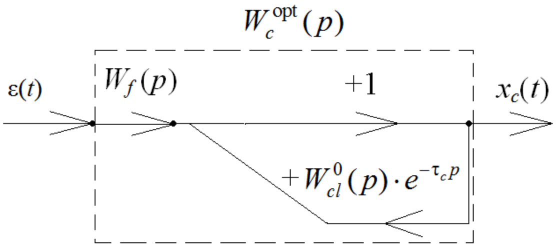

Fig. 2. Optimal regulator signal graph: $W_c^{\text{opt}}(p)$ – optimal regulator transfer function; $W_f(p)$ – filter transfer function; $W_{cl}^0(p)$ – part of closed-loop automatic control system's specified transfer function without delay time; ε(*t*) – control error; τ_c – delay time for controlling action channel

Transfer function of closed-loop automatic control system (criterion of optimality)

$$W_{y,x_{sp}}(p) = W_{cl}(p) = W_{cl}^0(p)e^{-\tau_c p} = \frac{W_c(p)W_{pl}(p)}{1+W_c(p)W_{pl}(p)}. \tag{8}$$

Optimal regulator transfer function under input step can be found with the help of equations (8) and (1)

$$W_c^{\text{opt}}(p) = \frac{W_{cl}(p)}{W_{pl}(p)\cdot\left[1-W_{cl}(p)\right]} = \frac{W_{cl}^0(p)}{W_{pl}^0(p)\cdot\left[1-W_{cl}(p)\right]} =$$

$$= W_f(p)\cdot\frac{1}{1-W_{cl}^0(p)\cdot e^{-\tau_c p}}, \tag{9}$$

where $W_f(p) = \frac{W_{cl}^0(p)}{W_{pl}^0(p)}$ – filter transfer function; $W_{pl}^0(p)$ – part of plant's transfer function without delay time.

Specified transfer function of closed-loop automatic control system, which is based on structure of plant's transfer function (1) (optimal input step criterion)

$$W_{cl}(p) = W_{cl}^0(p)e^{-\tau_c p} = \frac{e^{-\tau_c p}}{\left(T_{cl}p+1\right)^2}, \tag{10}$$

where T_{cl} – one and only one calculated dynamic adjustment setting of optimal regulator, which help to calculate regulation costs of automatic control system to the controlled variable step input.

Filter transfer function with the help of equations (1) and (10) is equal

$$W_f(p) = \frac{W_{cl}^0(p)}{W_{pl}^0(p)} = \frac{(Tp+1)(\sigma p+1)}{k\left(T_{cl}p+1\right)^2} = \frac{(101p+1)(19p+1)}{1{,}6\left(T_{cl}p+1\right)^2}. \tag{11}$$

The numerical value of T_{cl} is calculated with the help of golden ratio number sequence (third variant) [10]

$$T_{cl1} = 0.618\tau_c = 0.618 \cdot 11.2 = 6.92 \text{ s.} \tag{12}$$

The numerical value of T_{cl} must be increased to make maximum control action equals to automatized controller adjustment method with the help of Simulink MatLab API (fourth variant)

$$T_{cl2} = 0.725\tau_c = 0.725 \cdot 11.2 = 8.12 \text{ s.} \tag{13}$$

The tab. 1 gives dynamic adjustment settings for all four methods.

Table 1

Dynamic adjustment settings of four compared controllers

Number of variant	Name of method	Dynamic adjustment settings				
		k_c	T_i, s	T_d, s	T_b, s	T_{cl}, s
1	Automatized controller adjustment (Simulink MatLab API)	2.789	0.0246	38.67	0.40	–
2	Full compensation method in general terms	1.674	120.0000	11.20	1.12	–
3	Optimal regulator (T_{cl1} = 6.92 s)	–	–	–	–	6.92
4	Optimal regulator (T_{cl2} = 8.12 s)	–	–	–	–	8.12

Results of transient simulation

Fig. 3 shows control action variation in open-loop automatic control system for classic PID controller and optimal regulator (first and fourth adjustment variants).

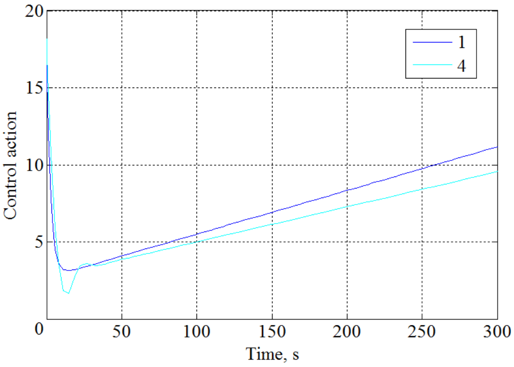

Fig. 3. Control action variation in open-loop automatic control system

Curves of control action variation in open-loop automatic control system are in close agreement for optimal and PID controllers as we can see on fig. 3.

Fig. 4 and 5 show controlled variable variation ($y(t)$) and control action variation ($x_c(t)$) to the controlled variable step input (x_{sp}).

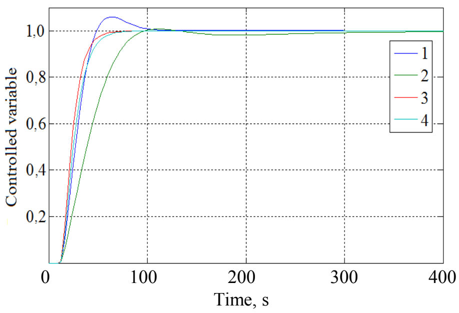

Fig. 4. Controlled variable variation to the controlled variable step input

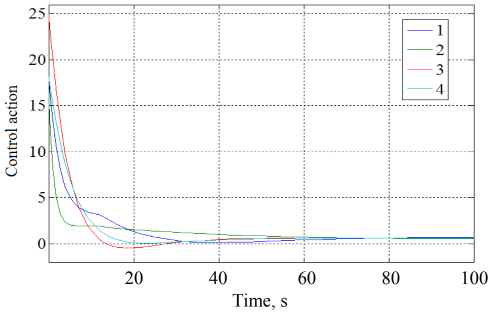

Fig. 5. Control action variation to the controlled variable step input

Fig. 6 and 7 show controlled variable variation ($y(t)$) to the internal disturbance (f_1) and external disturbance (f_2).

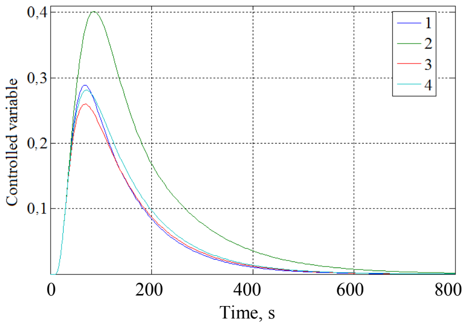

Fig. 6. Controlled variable variation to the internal disturbance

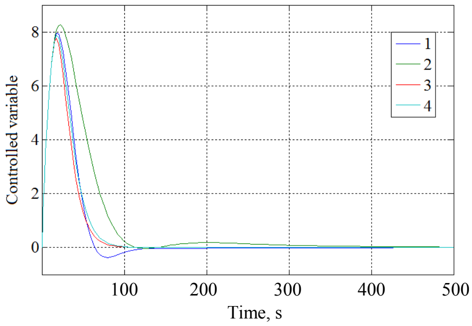

Fig. 7. Controlled variable variation to the external disturbance

The tab. 2 gives regulation costs of the automatic control systems to the controlled variable step input (x_{sp}), internal disturbance (f_1) and external disturbance (f_2).

Table 2

Transient regulation costs of four compared controllers

Variant	Kind of disturbance	t_c, s	$\sigma_{\max}$, %	$x_y^{\max}$	$\Delta y^{\max}$
1	x_{sp}	89	5.93	18.26	–
	f_1	340	–	–	+0.289
	f_2	98	–	–	+7.950
2	x_{sp}	88	0	16.74	–
	f_1	470	–	–	+0.401
	f_2	102	–	–	+8.260
3	x_{sp}	53	0	25.05	–
	f_1	350	–	–	+0,260
	f_2	73	–	–	+7.770
4	x_{sp}	60	0	18.19	–
	f_1	360	–	–	+0.281
	f_2	78	–	–	+7.890

Keys used: t_c – time, when controlled variable get to the controller's dead band (±2 %); $\sigma_{\max}$ – maximum overshoot; $x_y^{\max}$ – maximum control action variation; $\Delta y^{\max}$ – maximum dynamic controlled variable variation to the internal and external disturbances.

When regulation costs of four compared controllers (PID controllers and optimal regulators) were analyzed, it was found that fourth variant has the best regulation costs to the controlled variable step input, but third variant marginally better than fourth variant to the internal and external disturbances.

CONCLUSIONS

1. It has been suggested three variants of PID and optimal controller adjustment (number 2–4), which were compared with automatized adjusted controller (Simulink MatLab API) to the input step in automatic control system.

2. ACS automatized adjustment with the help of Simulink MatLab API didn't let to adjust controller in such a way that controlled variable varies monotonically without overshoot to input step.

3. If PID controller has non-free behavior (only controller coefficient and time constants are adjusted), then controller adjustment with the help of full compensation method in general terms (second variant) has some advantages compared to automatized adjustment (first variant). There are: no overshoot; time, when controlled variable get to the controller's dead band, is by a 1.1 % less and maximum control action variation is by a 8.3 % less to input step. But maximum dynamic controlled variable variation is by a 38.7 % larger and stabilization time is by a 38.2 % larger than first variant to the internal disturbance (f_1). And maximum dynamic controlled variable variation is by a 3.9 % larger and stabilization time is by a 4.1 % larger than first variant to the external disturbance (f_2).

4. If PID controller has free behavior (controller structure can be changed), then it is appropriate to use optimal controller transfer function for controller adjustment. Simulation results of transients show significant improvement of control quality to the controlled variable step input. Stabilization time is by a 40.4 % less (third variant) and by a 32.6 % less (fourth variant) than automatized controller adjustment (first variant). But maximum control action variation is by a 37.2 % larger for third variant and by a 1.0 % less for fourth variant. As well these variants have no overshoot.

5. First, third and fourth variants have virtually the same regulation costs to the internal disturbance f_1. Stabilization time is by a 2.9 % larger (third variant) and by a 5.9 % larger (fourth variant) than first variant. But maximum control action variation is by a 10.0 % less for third variant and by a 2.8 % less for fourth variant.

6. Use of optimal regulator let to improve regulation costs to the external disturbance f_2. Stabilization time is by a 25.5 % less (third variant) and by a 20.4 % less (fourth variant) than first variant. But maximum control action variation is by a 2.3 % less for third variant and by a 0.8 % less for fourth variant.

7. Controller design with the help of optimal regulator transfer function let to improve greatly transient regulation costs to the input step and disturbances and let to simplify adjustment process too, because of optimal regulator has one and only one dynamic adjustment setting. Curves of control action variation in open-loop automatic control system are in close agreement for optimal and PID controllers.

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