VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

Valerijus ZLOSNIKAS

DEVELOPMENT OF ASYMMETRIC CONTROLLERS FOR FREQUENCY CONVERTERS

SUMMARY OF DOCTORAL DISSERTATION

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Introduction

Topicality of the Problem

Many of technological processes and machines including technologies based on the AC induction motors controlled by the frequency converters are characterized by the asymmetric dynamics. The application of asymmetric controllers for control of such technological processes and machines allows us to improve the transient performance (to reduce the settling time and overshoot of transient) of the control system as compared with the case when popular in industry PI (Proportional-Integral) and PID (Proportional-Integral-Derivative) controllers are used. Additionally, the implementation of asymmetric controllers allows us to improve the transient performance of linear plants (technological processes and machines with the symmetric dynamics) as well. Consequently, implementation of the asymmetric controllers allows us to improve the control quality and reliability of technological processes and machines, therefore, the development and research works in this field of activity is topical and has practical value. Directly the topicality of works is proved by the interest of industry in the development of the asymmetric controllers, which is reflected by the projects, during accomplishment of which the results presented in the dissertation were obtained.

Object of Research

Asymmetric controllers for control of technological processes and machines.

The Aim of the Work

The aim is to develop asymmetric controllers, which allow us to improve the transient performance of the control systems of technological processes and machines (in the following material – plants) as compared with the case when PI and PID controllers are used.

Tasks of the Work

The following tasks have to be solved to achieve the aim of the work:

1. Create the algorithms of the asymmetric controllers for control of plants with the asymmetric dynamics and linear plants.
2. Investigate the control systems of the plants with the asymmetric dynamics based on the asymmetric controllers.
3. Investigate the control systems of the linear plants based on the asymmetric controllers.

4. Investigate the stability of control systems based on the asymmetric controllers.

Methods of Research

The simulation and experimental investigation were applied in the work. Simulation was performed using *Simulink* and *Spice* programs. The experimental investigations have been performed using the experimental model of asymmetric controllers and HIL (*Hardware in the Loop*) technique. The experiments using the stand of ventilation system with the AC induction motor drive of fan supplied by the frequency converter were provided as well. The program of microcontroller, which implements the asymmetric controllers, was created using assembler programming language.

Scientific Novelty of Work

The following scientific novelties to the field of Electrical and Electronics Engineering were disclosed:

1. The new control algorithms of asymmetric controllers, which allow us to improve the transient performance of the control systems of plants with the asymmetric dynamics and linear plants as compared with the case when popular in industry PI (Proportional-Integral) and PID (Proportional-Integral-Derivative) controllers are used, were created:

– asymmetric Proportional-Integral;

– asymmetric Proportional-Integral-Derivative.

2. The new model of plant with the time constant asymmetry based on the standard Simulink functional blocks was developed.

Practical Value

The results of the dissertation were applied for the development of controllers for the control of speed of fans of energy saving ventilation systems and water pumps of water supply systems with the AC induction motor drives supplied by the frequency converters.

The works of the dissertation are related with the following projects:

Projects financed by industry

1. The development of specialized frequency converter for control of advanced ventilation systems fan motors. 2007–2010, contract No. U-2007/8, head A. Baškys, contracting authority JSC “Ventmatika”.

2. The development of frequency converter for advanced water supply systems. 2011–2012, contracts No. 308-S095 and 3400-S155, head A. Baškys, contracting authority JSC “Tamona”.

High technology development programme projects

3. The investigation and development of frequency converters and their introduction into the serial production. 2007–2009, contract No. B-13/2007, head A. Baškys, contracting authority Lithuanian State Science and Study Foundation (LVMSF).

4. Development of specialized frequency converter for the serial production. 2012–2013, No. 31V-37 (2012), No. 31V-35 (20132), head A. Baškys, contracting authority Agency for Science, Innovation and Technology (MITA).

Defended Propositions

1. The developed asymmetric aPI and aPID controllers as compared to the PI and PID controllers allow us for the analyzed plants with the asymmetric dynamics to reduce 1.2–6 times the set point step response transient settling time and 5–20 times the overshoot, and 1.2–4 times the settling time of transient caused by the load disturbance.
2. The developed asymmetric aPI and aPID controllers as compared to the PI and PID controllers allow us for the analyzed linear plants to reduce 1.5–5 times the positive load disturbance response transient settling time without worsening of set point change response transient performance.
3. The linear and non-linear parts of control systems with the asymmetric controllers can be separated and, as consequence, the Popov stability criteria and its modifications can be applied only for the linear plants control systems based on aP and PaI controllers.

The Scope of the Scientific Work

The thesis is presented in the Lithuanian language. It consists of introduction, four chapters and the list of 93 references. The thesis comprises 95 pages, 68 figures, 27 formulas and 2 tables.

1. Control problems of plants with the asymmetric dynamics and linear plants using Proportional-Integral and Proportional-Integral-Derivative controllers

The concept of object with the asymmetric dynamics is defined. The Control problems of plants with the asymmetric dynamics and linear plants using PI and PID controllers are analyzed. The problem of simulation of plant with the time delay asymmetry is discussed. The conclusions of the first chapter of dissertation are presented and dissertation tasks are formulated.

The object with the asymmetric dynamics is object, which has different dynamics during the rise and fall of plant output parameter, i.e. the object for the transfer function of witch the following inequality is valid:

$$G_{\mathrm{a}}(s)\Big|_{\mathrm{d}Y_{\mathrm{a}}(t)/\mathrm{d}t \geq 0} \neq G_{\mathrm{a}}(s)\Big|_{\mathrm{d}Y_{\mathrm{a}}(t)/\mathrm{d}t < 0}, \qquad (1)$$

where $G_a(s)$ is transfer function of object with the asymmetric dynamics, dY_a is the output parameter of the plant and t is time. The plants with the asymmetric dynamics are often found in ventilation and water supply control systems.

The transfer function of plant in the general case can be presented as $G(s) = e^{-Ts}/(\tau s+1)^n$ where τ is time constant, T is plant response delay and n is transfer function order. The plants with the dynamics asymmetry caused by the asymmetry of τ and T are analyzed in the work. Additionally, the plants with the actuator rate limitation asymmetry, which is typical for the plants based on the AC induction motor drives supplied by the frequency converters, are investigated.

The unit set point step response ($Y_d(t)$ =1) followed by the $Y_d(t)$ drop ($Y_d(t)$ = 0.5) of the closed control system (Fig. 1) with the PID controller for the plant with the τ asymmetry presented by the transfer function (2) was simulated using electronic circuits simulation program *Spice*.

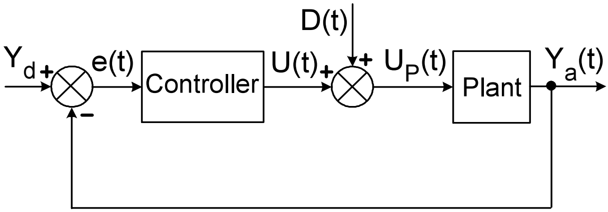


Fig. 1. Block diagram of the control system

$$G_1(s) = \frac{e^{-2s}}{(\tau s+1)^3}, \quad \tau = \begin{cases} 5, & \mathrm{d}Y_{\mathrm{a}}(t)/\mathrm{d}t \geq 0 \\ 1, & \mathrm{d}Y_{\mathrm{a}}(t)/\mathrm{d}t < 0 \end{cases}. \qquad (2)$$

The obtained results for different values of controller parameters – proportional (K_p), integral (K_i) and derivative (K_d) constants are presented in Fig. 2. The dependences are calculated for the cases when parameters of the PID controller are adjusted for dynamics of the plant transfer function associated with τ = 1 and τ = 5. It is seen that the PID controller provides a good unit step and $Y_d(t)$ drop response if controller parameters are in agreement with the plant dynamics. For example, the PID controller adjusted for dynamics of the plant transfer function associated with τ = 5 gives short settling time (t_s) and low overshoot (M_s) of the unit step response of the control system (Fig. 2., solid line). However, unacceptably long t_s in such a case characterize the $Y_d(t)$ drop response. On the other hand, the PID controller adjusted for dynamics of the plant transfer function associated with τ = 1 guarantees low M_s and short t_s of $Y_d(t)$ drop response but gives unacceptably high M_s and long t_s of the unit step response (Fig. 2, dashed line).

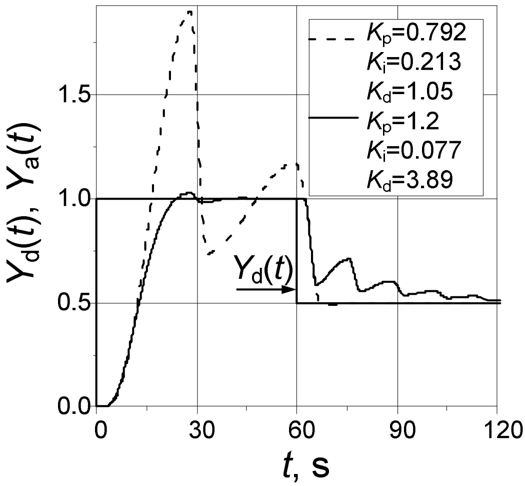


Fig. 2. The set point unit step response followed by the $Y_d(t)$ drop of the control system with plant $G_1(s)$ based on the PID controller adjusted for dynamics of the plant transfer function associated with τ = 5 (solid line) and τ = 1 (dashed line)

The simulation of the plant with the τ asymmetry using a standard transfer function block of the generally accepted program Simulink is complicated. It may appear that the value of the τ in equations (2) could be switched by employment of the network that contains two transfer function blocks with different τ values and a switch. However, this way of problem solution is not correct because the switching of transfer functions can cause the jumps of $Y_a(t)$ that in fact does not exist. Therefore, it is desirable to develop the adequate model of objects with the τ asymmetry based on the standard functional *Simulink* program blocks.

The set point change response usually is followed by the load disturbances in practice of control systems. It is desirable that the transient performance of the set point change response and load disturbance response would be as good as possible. To achieve good load disturbance response transient performance the integral constant of the PI and PID controller must be maximized. However, often this causes the increase of the overshoot and settling time (worsens the transient performance) of the set point response of control system. Because of this in the general case the PI and PID controllers does not allow us to achieve best possible transient performance of the control system response caused by the set point change and load disturbance at the same time.

The stability analysis of nonlinear control systems is complicated because does not exist the complete theory of nonlinear control systems analysis. There are several trends and lot of methods in nonlinear control systems stability research. The methods of nonlinear system stability analysis based on the frequency domain criterion, which are introduced by Popov, can be used for the analysis of control systems based on the asymmetric controllers. They are dedicated for the systems with the one nonlinear element, for the case when it is time invariant and the characteristic of this element is inside of some sector. The *Popov* criterion and its modifications *Cycle* and *Off-axis* methods can be used if the linear and nonlinear part of the control system can be separated. In the case of the control systems based on the asymmetric controllers this can be made only in the situations when the linear plants are controlled.

2. Asymmetric controllers for the control of plants with the asymmetric dynamics

The control algorithms of proposed, asymmetric PI (aPI), Proportional–asymmetric Integral (PaI) and asymmetric PID (aPID) controllers are described. The results of investigation of asymmetric dynamics objects control systems based on these controllers are presented and analyzed.

The investigation results show that in case of control of plants with the asymmetric dynamics the PI and PID controllers cannot at the same time provide best transient performance of control system response during the rise and fall of plant output parameter. Knowing that the parameters of the controller that guarantee best transient performance at different dynamics of the plant are different, it is logical to commute the values of controller constants. The problem is how to estimate the moments when the controller parameters should be switched. The sign of $\mathrm{d}Y_a(t)/\mathrm{d}t$ could be one of possible criteria. However, in case of plants with the response delay the response of $\mathrm{d}Y_a(t)$ and consequently the response of $\mathrm{d}Y_a(t)/\mathrm{d}t$ are delayed. Because of this, the values of controller parameters would also be switched with the delay and the behavior of the control system during the delay period would be determined by the previous values, which are determined by the previous situation. This can cause increased uncertainty of the control system operation.

The variation of set point $Y_d(t)$ changes the value of $e(t)$ without delay. During the positive step response $e(t)$ is predominantly positive and during the negative step response – negative. Consequently, the sign of $e(t)$ could be considered as indicator for estimation of the control system state and the parameters of controller should be switched at instants when the sign of $e(t)$ changes. Using this idea, the PID control algorithm, which has the different values of parameters at positive and negative $e(t)$, can be presented as follows:

$$U(t) = K_p(\mathrm{t})\, e(t) + \int_{t_0}^{t} K_i(\tau)\, e(\tau)\, d\tau + K_d(t)\frac{de(t)}{dt},$$

$$K_p(\mathrm{t}) = K_{pp},\;\; K_i(\tau) = K_{ip},\;\; K_d(\mathrm{t}) = K_{dp} \,\big|\, e(t) \ge 0\,, \tag{3}$$

$$K_p(\mathrm{t}) = K_{pn},\;\; K_i(\tau) = K_{in},\;\; K_d(\mathrm{t}) = K_{dn} \,\big|\, e(t) < 0\,,$$

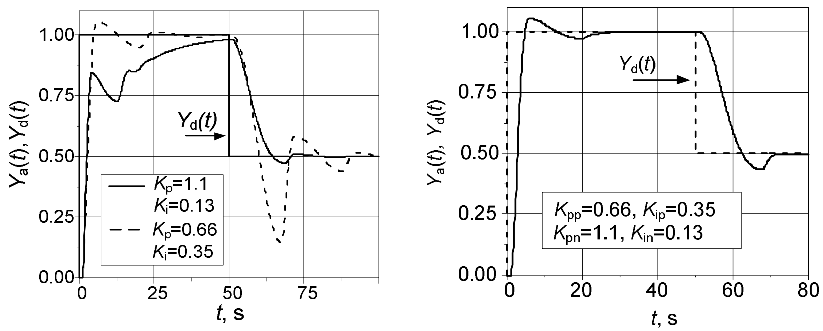
where K_{pp}, K_{ip}, K_{dp} and K_{pn}, K_{in}, K_{dn} are proportional, integral and derivative constants that act at positive and at negative $e(t)$, respectively, t_0 is point in time at which the algorithm starts to operate. In specific case, when $K_{pp} = K_{pn}$, $K_{ip} = K_{in}$ and $K_{dp} = K_{dn}$, algorithm (3) coincides with the algorithm of PID controller. The proportional, integral and derivative constants change their discrete values at instants in time at which $e(t)$ changes the sign. Therefore, they are time dependent in algorithm (3), i. e. in fact they are not constants.

The impact on the plant of the PID controller based on algorithm (3) is different at positive and negative $e(t)$ in the general case, i.e. it is asymmetric. Because of this, the controller with this property can be called the asymmetric PID (aPID).

The control algorithm of proposed asymmetric PI (aPI) controller is specific case of aPID algorithm (3) when constants K_{dp}, $K_{dn} = 0$ and algorithm of Proprtional-asymmetric Integral (PaI) controller is specific case of aPI controller when constants $K_{pp} = K_{pn}$.

The operation of the proposed aPI and aPID controllers was analyzed in the control systems of objects characterized by the asymmetric dynamics caused by the time constant asymmetry. The response transients of control systems of plants with the asymmetric dynamics based on the proposed asymmetric controllers are presented in Figs. 3 and 4. They are obtained using programs *Spice* and *Simulink*.

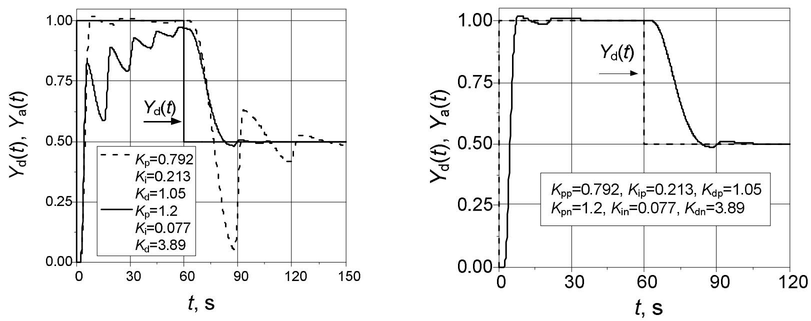
It is seen that employment of aPI and aPID controllers instead of PI and PID enables improving the transient performance of the analyzed control systems with plants that have asymmetric dynamics. Quantitative evaluation shows that



a) b)

Fig. 3. Set point unit step response followed by the $Y_d(t)$ drop of the control system with plant $G(s) = e^{-1s}/(\tau\, s+1)^2$ (τ =1, when $\mathrm{d}Y_a(t)/\mathrm{d}t \geq 0$ and τ = 5, when $\mathrm{d}Y_a(t)/\mathrm{d}\,t < 0$) based on the PI controller (a) adjusted for dynamics of plant associated with τ = 1 (dashed line) and τ = 5 (solid line) and aPI controller (b)

developed controllers as compared to the PI and PID controllers allow us for the analyzed plants with the asymmetric dynamics to reduce 1.4–6 times the set point step response transient settling time and 5–20 times the overshoot, and 1.2–3.1 times the settling time of transient caused by the load disturbance.



a) b)

Fig. 4. Set point unit step response followed by the $Y_d(t)$ drop of the control system with plant $G(s) = e^{-2s}/(\tau\, s+1)^3$ (τ = 1, when $\mathrm{d}Y_a(t)/\mathrm{d}t \geq 0$ and τ = 5, when $\mathrm{d}Y_a(t)/\mathrm{d}t < 0$) based on the PID controller (a) adjusted for dynamics of plant associated with τ = 1 (dashed line) and τ = 5 (solid line) and aPID controller (b)

The control systems of objects characterized by the asymmetric dynamics caused by actuator rate limitation and plant response delay were investigated as well. The obtained results show that employment of aPI and aPID controllers instead of PI and PID enables improving the transient performance of the analyzed control systems.

3. Application of asymmetric controllers for control of linear plants

The investigation results of control systems of linear plants based on the aPI, aPID controllers and PID controller with the set point observation are presented. The load disturbance response of control systems has been analyzed.

In most control systems the primary design goal is to reject the load disturbances. However, in cases when PI and PID controllers are used it is impossible to achieve a good load disturbance rejection and a good set point change response at the same time.

Let us analyze the feedback control system (Fig. 1) of the linear plant based on the PI controller. The unit step response ($Y_d(t) = 1$) followed by the positive unit disturbance ($D(t) = 1$) of the control system for different values of controller constants K_p and K_i is presented in Fig. 5. The dependences were computed using the dynamic system simulation program *Simulink*.

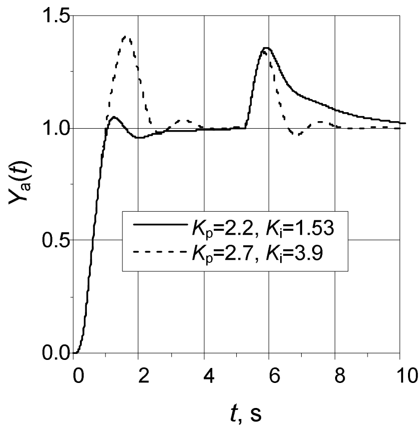


Fig. 5. Set point unit step response followed by positive unit disturbance of control system of plant $G(s) = e^{-0.3s}/(s+1)$ based on PI controller with different values of constants K_p and K_i

The dependence presented by solid line (Fig. 5) corresponds to the PI controller, which provides good set point step response transient performance (short settling time and low overshoot) of set point step response. However, the PI controller that guarantees good set point step response transient performance disapproves the load disturbance transient (solid lines in Fig. 5). The best load disturbance response transient performance (shortest setling time of transient) is achieved at higher values of K_p and K_i but in such a case the set point step response transient has large oversoot and long settling time (dashed lines in Fig. 5). It is desirable to find the solution that enables the load disturbance response transient performance of the control system to be improved without sacrificing the unit step response dynamics.

The set point unit step response followed by positive unit disturbance of linear plant control system based on the aPID controller is given in Fig. 6. Additionally, the control system response for the PID controller-based control system is presented.

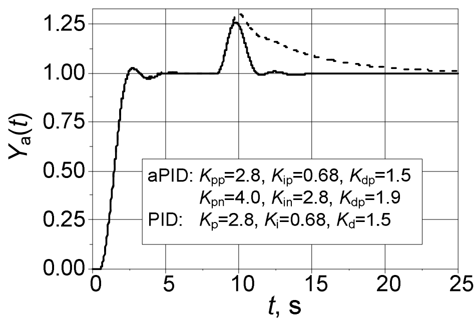


Fig. 6. Set point unit step response followed by positive unit disturbance of control system of plant $G(s) = e^{-0.5s}/(s+1)^2$ based on aPID and PID controllers. The PID controller constants are tuned for good set point step response transient performance

It is seen (Fig. 6) that employment of aPID controller for control of investigated plant allows us to tangibly improve the positive load disturbance response transient performance as compared with case when systems are based on PID controller, respectively, adjusted for good set point step response transient performance. On the other hand, it is evident that the transient of the set point step response of control system based on aPID controller is practically the same as compared to PID one (Fig. 6). Consequently, during the set point step response the aPID controller behaves in a similar way as PID controller adjusted for good set point step response transient performance and during the positive load disturbance – as the PID tuned to the best load disturbance response dynamics.

The control systems of linear plants based on the aPI controller were investigated as well. The obtained results show that employment of aPI controller instead of PI enables to improve positive load disturbance rejection of the analyzed control systems.

The aPI and aPID controllers provide good load disturbance response transient performance for the positive disturbances only. The proposed PID controller with the set point observation is provided with the additional information that allows the controller to know if the control system was disturbed by the set point change or not and enables it to operate with different parameters during the set point change response and the load disturbance response. The structure of such a control system is presented in Fig. 7. and the results of simulation of control system response transient – in Fig. 8.

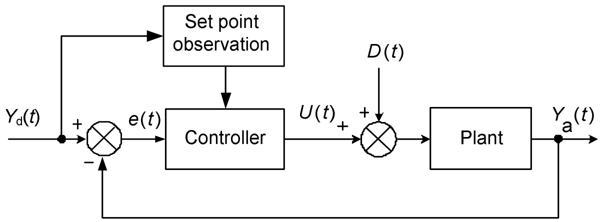


Fig. 7. The block diagram of the control system with the set point observation

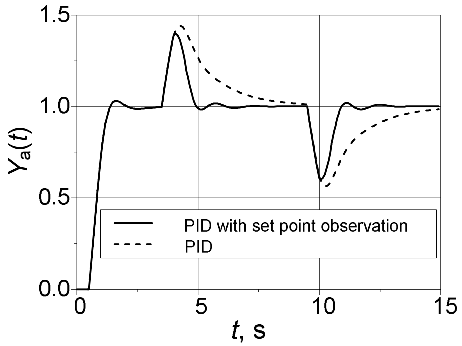


Fig. 8. Set point unit step response followed by positive and negative unit load disturbances of the control system of plant $G(s) = e^{-0.5s}/(1+s)$ with a PID controller and PID controller with the set point observation. The constants of PID controller with the set point observation $K_{ps} = 1.60$, $K_{is} = 1.17$, $K_{ds} = 0.20$, $K_{pd} = 2.60$, $K_{id} = 3.20$, $K_{dd} = 0.45$ and the constants of PID controller $K_p = 1.60$, $K_i = 1.17$, $K_d = 0.20$

It is seen that employment of the control system structure with the set point observation allows us to improve the load disturbance response transient performance of analyzed plants as compared to the case when a classical closed-loop structure is used.

4. Stability analysis and experimental investigation of control systems with the asymmetric controllers

The stability analysis results of the control systems based on the asymmetric controllers are presented. The results of experimental investigation of such a control systems using HIL (*Hardware In the Loop*) technique and experimental stand of ventilation control system are given.

The stability analysis was provided for control systems of linear plants based on the asymmetric Proportional (aP) and PaI controllers. The modifications of *Popov* stabilty criterion as *Circle* and *Off-axis* criterions were used for this purpose. The obtained results prove the fact that the *Circle* and *Off-Axis* criterions define only sufficient but not obligatory stability condition of the nonlinear control system. The plots for the stability analysis of the linear plant control system based on the PaI controller are given in Fig. 9.

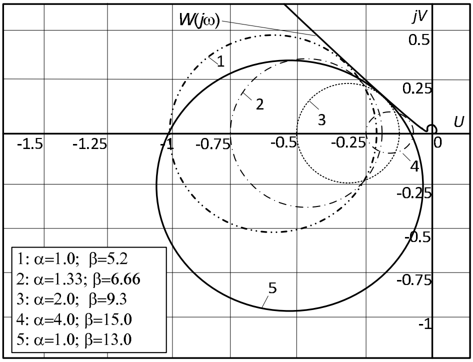


Fig. 9. The stability analysis plots using *Circle* and *Off-axis* criteria for the control system with the plant $G(s) = 3(s+1)/s^2(s^2+s+25)$ and PaI controller

The control system of plant with the time constant asymmetry based on the aPI controller was investigated using HIL technique. The employed HIL technique enables us to investigate the operation of designed actual controller using model of controlled plant, which is implemented using software *Simulink*. The model of plant was created using proposed first order plant model with the time constant asymetry (Fig. 10a).

The proposed PaI controller was investigated experimentally using stand of ventilation control system. The set point pulse and load disturbance response of the control system based on the PaI and PI controllers is presented in Fig. 10b.

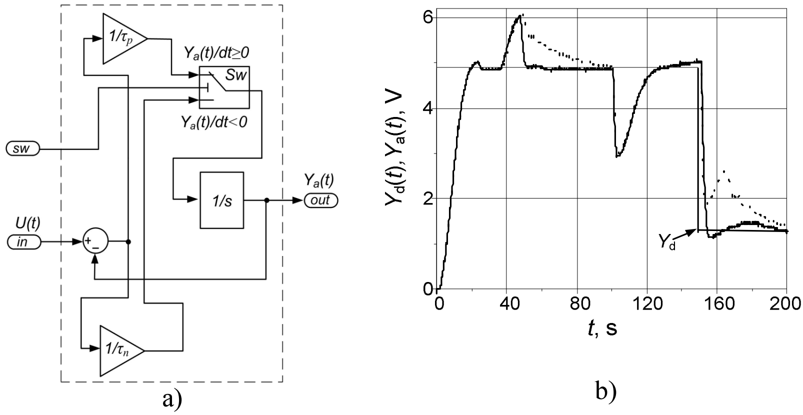


Fig. 10. The model of 1-st order plant with the time constant asymmetry for the software *Simulink* (a) and set point pulse and load disturbance response of the control system based on the aPI (solid line) and PI (doted line) controllers (b). The plant transfer function $G(s) = e^{-1s}/(\tau s+1)^2$ ($\tau = 2$ when $dY_a(t)/dt \geq 0$ and $\tau = 0.2$, when $dY_a(t)/dt < 0$). The PI controller parameters ($K_p = 0.8$, $K_i = 0.1$) are adjusted to dynamics of the plant, which corresponds to the rise of plant parameter. Constants of aPI controller: $K_{pp} = 0.8$, $K_{pn} = 0.5$, $K_{ip} = 0.1$, $K_{in} = 0.5$

The obtained transient indicate that PaI controller as compared to PI controller allow us to reduce 3–4 times disturbance response settling time of analyzed control system.

General conclusions

1. Many of control plants are characterized by the asymmetric dynamics. Popular in industry PI and PID controllers do not allow us to achieve the best behaviour of control systems with the plants that are characterized by the asymmetric dynamics
2. The developed aPI and aPID controllers constants are variable. The values of constants are switched at the moments, at which the sign of plant output parameter time derivative or control error changes. Asymmetric controller's constants can be adjusted by using the PI and PID adjusting rules.
3. The aPI controller as compared to the PI allows us for the analyzed plants with the asymmetry of time constant, actuator rate limitation and response delay to reduce 1.2–6 times the set point step response transient settling time and 5–14 times the overshoot, and 1.2–4 times the settling time of transient caused by the positive load disturbance.

4. The aPID controller as compared to the PID allows us for the analyzed plants with the time constant to reduce 6 times the set point step response transient settling time and 20 times the overshoot, and 1.2–2 times the settling time of transient caused by the positive load disturbance.

5. The application of aPI and aPID controllers for the analyzed linear plants as compared to the PI and PID allow us to reduce 1.5–3 and 2–5 times, respectively, the settling time of transient caused by the positive load disturbance without worsening the set point change response transient performance.

6. The employment of PID controller with the set point observation for the analyzed linear plants as compared to the PID allows us to reduce 2–3 times the settling time of transient caused by the positive and negative load disturbances.

7. The *Popov*, *Circle* and *Off-Axis* stability criteria can be applied for the linear plants control systems based on the aP and PaI controllers only because for these control systems the linear and non-linear parts can be separated.

8. The obtained results of experimental investigations indicate that aPI and PaI controllers as compared to the PI allow us to reduce 1.6 – 4 times the set point step and load disturbance response transient settling time of analyzed plants with the asymmetry of time constant and actuator rate limitation.

List of published papers on the topic of the dissertation

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Baskys A.; Zlosnikas V. 2006. Control of plants with asymmetric dynamics, *Elektronika i sviaz*, No 2, p. 49–53. ISSN 1811-4512.

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About the Author

Valerijus Zlosnikas was born in Vilnius on 11of June, 1980. Bachelor's degree in Electrical and Electronic Engineering, Faculty of Electronics, Vilnius Gediminas Technical University, in 2002. Master of Science in Electrical and Electronic Engineering, Faculty of Electronics, Vilnius Gediminas Technical University, in 2006. In 2009–2013 – PhD student at Department of Computer Engineering of Vilnius Gediminas Technical University. At present – Assistant in Department of Computer Engineering of Vilnius Gediminas Technical University and junior research associate in Electronic Systems Laboratory of State Research Institute Center for Physical Sciences and Technology.

DAŽNIO KEITIKLIŲ ASIMETRINIŲ REGULIATORIŲ KŪRIMAS IR TYRIMAS

Problemos formulavimas

Sparčiai vystantis elektronikai ir automatinio valdymo teorijai, automatinio valdymo sistemos vis plačiau taikomos technologijų ir įrenginių valdymui. Jų taikymas leidžia didinti darbo našumą, gaminių kokybę ir taupyti energiją.

Tyrimai rodo, kad dalis realių valdomųjų objektų turi asimetrinę dinamiką, t. y. skirtingą valdomojo objekto dinamiką, valdomajam parametrui didėjant ir mažėjant. Kalbant matematinėmis sąvokomis, asimetrinės dinamikos objekto perdavimo funkcijos, jei ji egzistuoja, parametrai arba pati funkcija keičiasi, keičiantis valdomojo parametro laiko išvestinės ženklui, t. y. šie objektai yra netiesiniai. Tokiomis savybėmis, pavyzdžiui, pasižymi energiją tausojančios vėdinimo sistemos, suskystintų dujų ir vandens tiekimo sistemos bei insulino, žmogui sergančiam diabetu, dozavimo sistema. Pramonėje plačiai naudojami, PI (proporcinis-integralinis) ir PID (proporcinis-integralinis-diferencialinis) valdymo algoritmus realizuojantys, reguliatoriai gerai tinka valdyti simetrinės dinamikos procesus, nes jų poveikis valdomajam objektui yra simetrinis, t.y. valdymo paklaidai padidėjus arba sumažėjus ta pačia verte, reguliatoriaus formuojamas valdymo signalas savo absoliutine verte pakinta tiek pat. Šiais reguliatoriais taip pat įmanoma pasiekti priimtinų valdymo kokybės rodiklių (valdymo sistemos atsako pereinamojo proceso trukmę ir perreguliavimą), esant santykinai mažai valdomojo objekto dinamikos asimetrijai. Tačiau didėjant objekto dinamikos asimetrijai, sistemos su minėtais reguliatoriais valdymo kokybės rodikliai blogėja ir tampa nepriimtini, o atskirais atvejais apskritai neįmanoma pasiekti stabilaus valdymo sistemos darbo.

PI ir PID reguliatoriai taip pat neleidžia tuo pat metu pasiekti geriausių atsako į valdymo sistemos nuostato pokytį ir į valdomojo objekto trikdį pereinamųjų procesų kokybės rodiklių, valdant tiesinius objektus.

Šiame darbe siūlomi ir tiriami asimetriniai reguliatoriai, kurių poveikis valdomajam objektui yra asimetrinis. Jie, lyginant su PI ir PID reguliatoriais, leidžia gauti geresnius objektų su asimetrine dinamika valdymo kokybės rodiklius. Taip pat, lyginant su PI ir PID reguliatoriais, jie leidžia pagerinti ir tiesinių objektų valdymo sistemų atsako į trikdį kokybės rodiklius. Darbo rezultatai panaudoti kuriant reguliatorius dažnio keitikliams technologijų su asinchroninių variklių pavaromis valdymui, reguliuojant variklio sukimosi greitį.

Darbo aktualumas

Daugelis technologinių procesų ir įrenginių, tame tarpe ir technologijų su asinchroninių variklių pavaromis, kurių sukimosi greitis yra valdomas dažnio keitikliais, turi asimetrinę dinamiką. Asimetrinių reguliatorių taikymas, lyginant su šiuo metu naudojamais PI ir PID reguliatoriais, tokių technologinių procesų ir įrenginių automatinio valdymo sistemose leidžia pagerinti valdymo kokybės rodiklius, o to pačiu ir valdomos technologijos ar įrenginio darbo kokybę ir patikimumą. Šie reguliatoriai taip pat leidžia pagerinti ir tiesinių objektų (objektų turinčių simetrinę dinamiką) valdymo kokybės rodiklius, todėl darbai pasirinktoje tyrimų srityje yra aktualūs ir turi praktinę vertę.

Disertacijoje pateiktų darbų aktualumą įrodo Lietuvos įmonių užsakomieji darbai ir Lietuvos valstybinio mokslo ir studijų fondo bei Mokslo inovacijų ir technologijų agentūros finansuoti Aukštųjų technologijų plėtros programos projektai, kuriuos vykdant buvo gauti disertacijoje pateikti tyrimų rezultatai.

Tyrimų objektas

Darbo tyrimų objektas yra asimetriniai reguliatoriai technologinių procesų ir įrenginių valdymui. Tiriamų reguliatorių specifinis bruožas yra tas, kad reguliatorių parametrų vertės yra diskretiškai keičiamos, pasikeitus valdomo parametro laiko išvestinės arba valdymo paklaidos ženklui. Darbe tiriami asimetrinis PI (aPI) ir asimetrinis PID (aPID) reguliatoriai.

Darbo tikslas

Šio darbo tikslas – sukurti ir ištirti asimetrinius reguliatorius, kurie lyginant su šiuo metu naudojamais PI ir PID reguliatoriais, leidžia pagerinti technologinių procesų ir įrenginių (toliau valdymo objektų) valdymo kokybės rodiklius.

Darbo uždaviniai

Darbo tikslui pasiekti išspręsti šie uždaviniai:

1. Sudaryti valdymo algoritmus asimetriniams reguliatoriams objektų su asimetrine dinamika ir tiesinių objektų valdymui.
2. Ištirti asimetrinių reguliatorių darbą valdant objektus su asimetrine dinamika.
3. Ištirti asimetrinių reguliatorių darbą valdant tiesinius objektus.
4. Ištirti valdymo sistemų su asimetriniais reguliatoriais stabilumą.

Tyrimų metodika

Darbe taikomi kompiuterinio modeliavimo ir eksperimentinio tyrimo metodai. Modeliavimas atliktas *Simulink* ir *Spice* programomis. Eksperimentiniai tyrimai atlikti naudojant reguliatorių, skirtų dažnio keitikliams, bandomuosius pavyzdžius ir HIL (*Hardware in the Loop*) tyrimo metodiką bei vėdinimo sistemos stendą su ventiliatoriaus dažnine asinchroninė pavara. Programos mikrovaldikliui, realizuojančiam sukurtus asimetrinius reguliatorius, sukurtos asemblerio programavimo kalba.

Darbo mokslinis naujumas

Rengiant disertaciją buvo gauti šie elektros ir elektronikos inžinerijos mokslui nauji rezultatai:

1. Sudaryti šie nauji valdymo algoritmai asimetriniams reguliatoriams, leidžiantys, lyginant su PI ir PID reguliatorių algoritmais, pagerinti objektų su asimetrine dinamika ir tiesinių objektų valdymo kokybės rodiklius:
   – asimetrinis proporcinis-integralinis;
   – asimetrinis proporcinis-integralinis-diferencialinis.
2. Sukurtas naujas objekto su laiko pastoviosios asimetrija modelis, kurį galima realizuoti standartiniais *Simulink* programos funkciniais blokais.

Darbo rezultatų praktinė reikšmė

Disertacijos rezultatai pritaikyti kuriant reguliatorius energiją tausojančių vėdinimo sistemų ventiliatorių ir vandens tiekimo sistemų siurblių pavarų asinchroninių variklių, maitinamų dažnio keitikliu, greičio valdymui. Disertacijos darbai susieti su šiais mokslo tiriamaisiais projektais:

Ūkio subjektų užsakomieji projektai

1. Specializuoto dažnio keitiklio, skirto pažangių ventiliavimo sistemų ventiliatorių elektros variklių valdymui, sukūrimas, užsakovas UAB „Ventmatika“, 2007–2010 m., vadovas A. Baškys, sutarties reg. Nr. U–2007/82 (panaudotas PaI reguliatorius).
2. Dažnio keitiklio, skirto pažangioms vandens tiekimo sistemoms, kūrimas, užsakovas UAB „Tamona“, 2011–2012 m., vadovas A. Baškys, sutarčių reg. Nr. 308-S095 ir 3400-S155 (panaudotas aPI reguliatorius).

Aukštųjų technologijų plėtros programos projektai

3. Dažnio keitiklių tyrimas, kūrimas ir įdiegimas į serijinę gamybą, 2007–2009 m., sutarties reg. Nr. B–13/2007–2009, vadovas A. Baškys, finansavo Lietuvos valstybinis mokslo ir studijų fondas (panaudotas PaI reguliatorius).
4. Specializuoto dažnio keitiklio sukūrimas serijinei gamybai, 2012–2013 m., Nr. 31V–37 (2012 m.), 31V–35 (2013 m.) vadovas A. Baškys, finansuoja Mokslo inovacijų ir technologijų agentūra (panaudotas aPI reguliatorius).

Ginamieji teiginiai

1. Sukurti asimetriniai aPI ir aPID reguliatoriai, lyginant juos su PI ir PID reguliatoriais, leidžia 1,6–6 kartus sutrumpinti tirtų asimetrinės dinamikos objektų valdymo sistemų atsako į nuostatos šuolį pereinamojo proceso trukmę, 5–20 kartų perreguliavimą ir 1,2–3,1 karto atsako į teigiamus trikdžius pereinamojo proceso trukmę.
2. Sukurti asimetriniai aPI ir aPID reguliatoriai, lyginant juos su PI ir PID reguliatoriais, leidžia 1,5–5 kartus sutrumpinti tirtų tiesinių objektų valdymo

sistemų atsako į teigiamą trikdį pereinamojo proceso trukmę, nebloginant atsako į nuostatos šuolį pereinamojo proceso kokybės rodiklių.

3. Tiesinių objektų valdymo sistemų su aP ir PaI reguliatoriais struktūroje įmanoma atskirti netiesinę ir tiesinę dalis, todėl šių sistemų stabilumo tyrimui gali būti taikomas Popovo kriterijus ir jo modifikacijos.

Darbo apimtis

Darbą sudaro įvadas, 4 skyriai, bendrosios išvados, literatūros sąrašas ir autoriaus publikacijų sąrašas. Bendra apimtis – 95 puslapiai, 69 iliustracijos, 2 lentelės, 29 numeruotos formulės ir 93 literatūros šaltinių.

Pirmajame skyriuje išanalizuota mokslinė literatūra skirta valdymo sistemoms su kintama struktūra ir apibrėžta objekto su asimetrine dinamika sąvoka. Aptariami valdymo sistemos kokybės vertinimo rodikliai. Nagrinėjamos objektų su asimetrine dinamika ir tiesinių objektų valdymo PI ir PID reguliatoriais problemos ir netiesinių valdymo sistemų stabilumo tyrimo problema. Aptariama objektų su asimetrine dinamika modeliavimo problema. Pateikiamos pirmojo skyriaus išvados ir formuluojami disertacijos uždaviniai.

Antrajame skyriuje aprašomi sukurti algoritmai asimetriniams PI (aPI) ir PID (aPID) reguliatoriams ir pateikiami asimetrinės dinamikos objektų valdymo sistemų su šiais reguliatoriais tyrimų rezultatai.

Trečiajame skyriuje aprašomi asimetrinių reguliatorių aPI, aPID ir PID reguliatoriaus su nuostatos stebėjimu tyrimo rezultatai, taikant juos tiesinių objektų valdymui, siekiant sumažinti valdymo sistemos atsako į trikdžius pereinamojo proceso trukmę.

Ketvirtajame skyriuje aprašomi valdymo sistemų su asimetriniais reguliatoriais stabilumo tyrimai. Pateikti asimetrinių aPI ir PaI reguliatorių eksperimentiniai tyrimų rezultatai, valdant asimetrinės dinamikos objektus.

Bendrosios išvados

1. Daugelio valdomųjų objektų dinamika yra asimetrinė, todėl plačiai pramonėje naudojami PI ir PID reguliatoriai, valdant objektus su asimetrine dinamika, neleidžia tuo pat metu pasiekti valdomojo parametro kokybiško pereinamojo proceso parametrui didėjant ir mažėjant.

2. Sukurti asimetriniai aPI ir aPID reguliatoriai su keičiamais koeficientais, kurių vertės yra diskretiškai pakeičiamos, keičiantis valdomojo parametro laiko išvestinės arba valdymo paklaidos ženklui ir kurių derinimui tinka PI ir PID reguliatorių derinimo principai.

3. aPI reguliatorius tirtiems objektams su laiko pastoviosios, vykdiklio tempo ribojimo ir vėlinimo asimetrija, lyginant su PI reguliatoriumi, leidžia 1,2–6 karto sumažinti atsako į nuostatos pokyčius pereinamojo proceso trukmę,

5–14 kartų perreguliavimą ir 1,2–4 karto atsako į teigiamus trikdžius pereinamojo proceso trukmę.

4. aPID reguliatoriaus taikymas objektų su laiko pastoviosios asimetrija valdymo sistemose vietoje PID reguliatoriaus, tiriamiems objektams 6 kartus sumažina valdymo sistemos atsako į nuostatos šuolius pereinamojo proceso trukmę, 20 kartų perreguliavimą ir 1,2–2 kartus atsako į teigiamus trikdžius pereinamojo proceso trukmę.

5. aPI reguliatoriaus taikymas tiesiniams objektams, lyginant su PI reguliatoriumi, leidžia analizuotiems objektams 1,5–3 kartus, o aPID reguliatorius, lyginant su PID reguliatoriumi, 2–5 kartus, sumažinti atsako į teigiamą trikdį pereinamojo proceso trukmę, nebloginant atsako į nuostatos šuolį pereinamojo proceso kokybės rodiklių.

6. PID reguliatoriaus su nuostatos stebėjimu vietoje PID reguliatoriaus taikymas tiesiniams objektams valdyti, 2–3 kartus sumažina analizuojamiems objektams atsako į teigiamą ir neigiamą trikdžius pereinamųjų procesų trukmes.

7. Naudojant Popovo, *Off-Axis* ir apskritiminį kriterijus, ištirti stabilumą įmanoma tik tiesinių objektų valdymo sistemoms su asimetriniais reguliatoriais, kurių struktūra turi tik vieną perjungėją, pvz. sistemos su aP ir PaI reguliatoriais, nes tik valdymo sistemoms su tokiais reguliatoriais įmanoma atskirti tiesinę ir netiesinę sistemos dalis

8. Atlikti eksperimentiniai tyrimai parodė, kad aPI ir PaI reguliatoriai, lyginant su PI, leidžia pasiekti 1,6–4 kartus trumpesnes atsako į nuostatos pokyčius ir trikdžius pereinamųjų procesų trukmes, valdant tirtus objektus su laiko pastoviosios ir vykdiklio tempo ribojimo asimetrija.

Trumpos žinios apie autorių

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VALERIJUS ZLOSNIKAS

DEVELOPMENT OF ASYMMETRIC CONTROLLERS
FOR FREQUENCY CONVERTERS

Summary of Doctoral Dissertation
Technological Sciences,
Electrical and Electronic Engineering (01T)

VALERIJUS ZLOSNIKAS

DAŽNIO KEITIKLIŲ ASIMETRINIŲ REGULIATORIŲ
KŪRIMAS IR TYRIMAS

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