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IMPROVEMENET OF CHARACTERISTICS OF DISCRETE-TIME VARIABLE STRUCTURE CONTROLLER FOR PLANTS WITH FINITE ZEROS

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ABSTRACT: The use theory of variable structure systems (VSS) to control plants with finite zeros by introducing discrete-time signal processing is analyzed in this paper. Dual-rate sampling time is considered: bigger in the main feedback loop and smaller in the process of commutation structure process. To improvement steady-state accuracy of the control systems with plants of zero type proportional plus integral (PI) control action in the VSS control algorithm was introduced. An example of the second order system with the possibilities of PI action introducing is given.
KEYWORDS: Discrete-time variable structure systems, Finite zeros, Proportional plus integral control action

INTRODUCTION

The paper deals with the discrete-time variable structure systems. This class of control systems is not widely studding. Only a few papers [1-15] treat the problems arisen in the VSS with discrete-time signal processing. In this paper the problem of organization quasi-sliding or discrete sliding mode (by using classical, equivalent control method or Lyapunov's function approach) in the systems which plants have not finite zeros, are analyzed. The problems of control plants with finite zeros, in class of discrete-time variable structure systems, up to now, are not studding. In this paper the purpose is to study the problems that arise in VSS assigned to regulation of second order plants with finite zeros.

Presence of finite zeros (differentiable action in the plant) leads to some problems in VSS synthesis, since breaking of control function and differentiability of plant, interruptions occur in the phase trajectories of the system. Existence of phase trajectories interruptions complicates to determination of conditions of origin and the existence of sliding modes, in the continuous-time and idiscrete-time VSS.

For the elimination of finite zeros influence, a cascade of first-order filters are introduced. if the plant parameters are variable, then the cascade of these filters is also encompassed by the commutation feedback. This method, for the continuous-time VSS, has been investigated by Kostyleva [16]. We chose also this method for the discrete-time VSS, for the following reasons:

- its simplicity,
- to make discrete-time VSS synthesis easier.
- the robustness of the VSS algorithms to plant parameter uncertainties.

We introduce dual-rate discrete-time signal processing with bigger sampling-time period in the main feedback loop and with very small sampling time in the realization of the structure commutation process, which may be neglected. Only controller type of system will be analyzed. First, the discrete-time mathematical system model will be given, and then, based on the general quasi-sliding (zig-zag) mode existence conditions [3], the relations for the VSS controller synthesis will be given. On a one example, the synthesis procedure and the computer simulation results should be given.

PROBLEM STATEMENT

The paper deals with the discrete-time variable structure system shown in Figure 1. It is supposed that all necessary information of the plant is accessible for measurement. The problem of measuring required state coordinates is a general one, which is also present in the system without finite zeros.

Generally, it can be practically resolved by using an observer. Because of that, we will further suppose that the plant is controllable and fully observable. The VSS formatter is the system structure commutator which is digital. Dual-rate sampling periods assumed: large (T), in the process of the control signal formation and small (T_S), in the process of obtaining switching conditions. It is assumed that $T_S << T$ and the effects of small sampling-time T_S may be neglected for further analysis. Because *of phase trajectories breaking a consequence of differentiability of plant, we should use the method of eliminating finite zero influence in the plant transfer function by introducing additional commutation filter of adequate time constant proposed by Kostylova [16] for the continuous-time VSS.*

The systems type regulator (r=const) is analyzed in this paper. Let us adopt r=0.

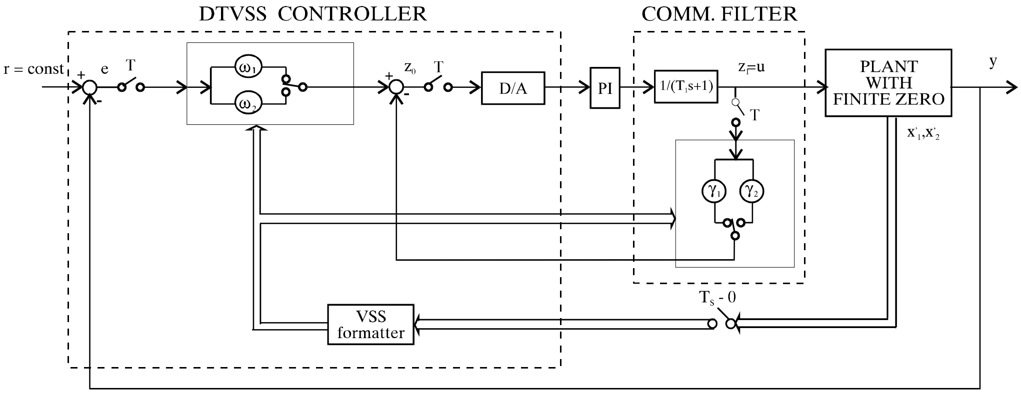

Figure 1. Variable structure control system block diagram

Mathematical model of the plant (Figure 1) was given in the form:

$$\dot{\mathbf{x}}(t) = \mathbf{A}\,\mathbf{x}(t) + \mathbf{b}\,u(t)$$
$$y(t) = \mathbf{c}\,\mathbf{x}(t) \tag{1}$$

where: - $\mathbf{x}(t) = \begin{bmatrix} x_1 & x_2 \end{bmatrix}^T$ *- the plant state vector in the phase space,*

- $y(t) = y$ *- the plant output variable,*

- u(t) = u - the controll signal.

- $\mathbf{A} = \begin{bmatrix} 0 & 1 \\ -a_1 & -a_2 \end{bmatrix}$, $\mathbf{b} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$, $\mathbf{c} = \begin{bmatrix} b_1 & b_2 \end{bmatrix}$,

- a_1, a_2, b_1, b_2 *- the plant parameters.*

Let us adopt as new the state coordinates of the system in Figure 1:

- $x_1 = e$ *- the system error,*

- $x_2 = \dot{e}$ *- the first derivative of the system error,*

which can be expressed by the following relations :

$$\begin{aligned} x_1 &= e = r - y = -\mathbf{c}\,\mathbf{x} \\ x_2 &= \dot{x}_1 = \dot{e} = -\dot{y} = -\mathbf{c}\,\mathbf{A}\,\mathbf{x} - \mathbf{c}\,\mathbf{b}\,u \end{aligned} \quad \Leftrightarrow \quad \dot{\mathbf{x}} = -\begin{bmatrix} \mathbf{c} \\ \mathbf{c}\,\mathbf{A} \end{bmatrix} \mathbf{x} - \begin{bmatrix} 0 \\ \mathbf{c}\,\mathbf{b} \end{bmatrix} \mathrm{u} \tag{2}$$

Taking into consideration relations (2), expressions for $\mathbf{x}$ *and* e_2 *assume the forms:*

$$\mathbf{x} = \begin{bmatrix} \mathbf{c} \\ \mathbf{c}\,\mathbf{A} \end{bmatrix}^{-1} \mathbf{x} - \begin{bmatrix} 0 \\ \mathbf{c}\mathbf{b} \end{bmatrix} \begin{bmatrix} \mathbf{c} \\ \mathbf{c}\,\mathbf{A} \end{bmatrix}^{-1} \mathrm{u}\,,$$

$$\dot{x}_2 = \ddot{x}_1 = -\ddot{e} = -\ddot{y} = \mathbf{c}\,\mathbf{A}^2 \begin{bmatrix} \mathbf{c} \\ \mathbf{cA} \end{bmatrix}^{-1} \mathbf{x} + (-\mathbf{c}\,\mathbf{A}\;\mathbf{b} + \mathbf{c}\,\mathbf{A}^2 \begin{bmatrix} 0 \\ \mathbf{c} \end{bmatrix} \begin{bmatrix} \mathbf{c} \\ \mathbf{c}\,\mathbf{A} \end{bmatrix}^{-1}) u \text{ - } \mathbf{c}\,\mathbf{b}\,\dot{u}$$

The mathematical model of the system in the new state coordinates system has the following form:

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = \mathbf{c}\,\mathbf{A}^2 \begin{bmatrix} \mathbf{c} \\ \mathbf{cA} \end{bmatrix}^{-1} \mathbf{x} + (-\mathbf{c}\,\mathbf{A}\,\mathbf{b} + \mathbf{c}\,\mathbf{A}^2 \begin{bmatrix} 0 \\ \mathbf{c} \end{bmatrix} u \begin{bmatrix} \mathbf{c} \\ \mathbf{c}\,\mathbf{A} \end{bmatrix}^{-1}) u \text{-} \mathbf{c}\,\mathbf{b}\,\dot{u} \quad \Leftrightarrow \quad \begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= -a_1\,x_1 - a_2\,x_2 - b_1\,u - b_2\,\dot{u} \end{aligned} \tag{3}$$

Based on relations (1) and (3), it can be concluded that the transformation matrix for transition from the mathematical model of the plant to the mathematical model of the system in the new state coordinates system is the unit matrix. From the practical point of view it means that the system error signal and its differential are not accessible for measuring purposes, the corresponding plant state coordinates can be applied. If the required plant state coordinates are not accessible for immediate measuring, some of the known methods for the plant state reconstruction (observer) can be applied.

We should use the method of eliminating finite zero influence by introducing additional analogous filter (aperiodical element of the first order) of adequate time constant T_1*, proposed by Kostyleve [16]. Mathematical model of the given system with additional commutation filter (Figure 1) was given in the form:*

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = -\sum_{i=1}^{2} a_i\, x_i - (b_2\, A_{0,1} + b_1) z_1 - b_2 A_{1,1} z_0$$
$$A_{0,1} = \frac{-1}{T_1}, \quad A_{1,1} = \frac{1}{T_1}, \qquad z_0 = \Omega\, x_1(kT) + \Gamma\, z_1(kT),$$
$$\Omega = \begin{cases} \omega_1 & for \quad x_1(kT_s) g(kT_s) > 0 \\ \omega_2 & for \quad x_1(kT_s) g(kT_s) < 0 \end{cases}, \quad \Gamma = \begin{cases} \gamma_1 & for \quad x_1(kT_s) g(kT_s) > 0 \\ \gamma_2 & for \quad x_1(kT_s) g(kT_s) < 0 \end{cases} \tag{4}$$
$$g(kT_s) = c_2 x_2(kT_s) + c_1 x_1(kT_s) \qquad T_s = T/d, \quad T >> T_s \to 0, \quad d - \text{integer}$$
$$c_1, c_2 = const > 0, \quad c_2 = 1, \quad c_1 = c$$

where are plant parameters.

$$a_{i\,\min} \le a_i \le a_{i\,\max,} \qquad i = 1,2;$$
$$b_{j\,\min} \le b_j \le b_{j\,\max}, \qquad j = 1,2;$$

Discrete-time VSS controller parameters $c, \omega_1, \lambda_1, \gamma_1$ *and* μ_1 *should be determined so that the zig-zag (quasi-sliding) movement mode will be occur in the system.*

In the phase of setting up the task of the discrete-time VSS synthesis, a problem of the system structure choice and regulator parameters for the purpose of achieving a desired character of behaviour and accuracy of operation in a steady-state may arise. The character of the behavior of the digital control system in the steady-state is determined by the type of the system with reference to the input signal, while the operation accuracy is determined by the error signal value, which is set up long enough after the moment of the system excitation by the determined standard input signal. The zero steady-state error should most frequently be achieved.

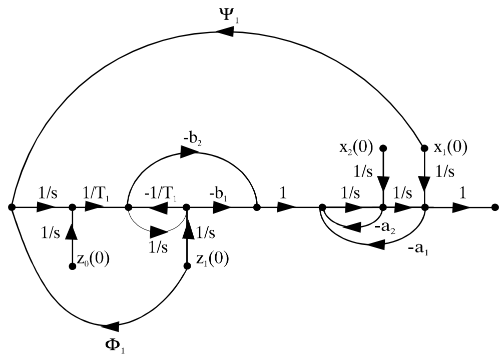

Figure 2. Signal flow graph for the variable structure control system

DETERMINING THE DIGITAL CONTROL PARAMETER

Shown in Figure 2 is the analyzed system signal flow graph. Based on this graph and Mason's rule, the discrete mathematical model of the given system (Fig.1.) can be obtained in the next form:

$$\mathbf{x}\big[(k+1)T\big] = \mathbf{H}(a,b,T,v)\,\mathbf{x}(kT) + \mathbf{L}(a,b,T,v)\,\mathbf{z}(kT) \tag{5}$$

where:

$$\mathbf{H} = \begin{bmatrix} A\Psi_1 j + \sum_{i=2}^{3} a_i w^{(i-1)} + B\sum_{i=2}^{3} a_i w^{(i-2)} & w^{(1)} + wB \\ A\Psi_1 w - a_1 w^{(1)} - Ba_1 w & w^{(2)} + w^{(1)} B \end{bmatrix}; \quad \mathbf{L} = \begin{bmatrix} -(b_1 + b_2 A_{0,1}) w + \Phi_1(-\frac{b_1}{T_1} j - b_2 A_{1,1} w) & 0 \\ -(b_1 + b_2 A_{0,1}) w^{(1)} + \Phi_1(-\frac{b_1}{T_1} w - b_2 A_{1,1} w^{(1)}) & 0 \end{bmatrix}$$

$$A = -\frac{b_1}{T_1} w - b_2 A_{1,1} w^{(1)}, \quad B = \frac{w}{T_1},$$

- $j = j(T) = w^{(-1)}(T)$ - *normal response of the plant with the additional analogous filter to Dirac impulse (normal term implies a zero initial conditions),*
- $w = w(T) = w^{(0)}(T)$ - *normal step response of the plant with the additional analogous filter,*
- $w^{(i)} = w^{(i)}(T)$ - *first derivative of the normal step response of the plant with the additional analogous filter.*

Sufficient conditions of the zig-zag mode existence on the hyperplane and of the stability of the whole system were derived in [2-5] in the form:

$$\lim_{g(kT)\to 0} \Delta g(kT) \le 0, \qquad \lim_{g(kT)\to 0} \Delta g(kT) \ge 0 \tag{6}$$

$$g(kT) = \sum_{i=1}^{n} c_i\, x_i(kT) = \mathbf{c}^T \mathbf{x}(kT), \quad k = 0,1,\dots n\,, \mathbf{c}^T = \begin{bmatrix} c & 1 \end{bmatrix} \tag{7}$$

$$\Delta g(kT) = g((k+1)T) - g(kT) \tag{8}$$

The condition (6) taking into consideration relations (5) and (7), expression (8) assumes the form of (9):

$$\Delta g(kT) = \mathbf{c}^T[\mathbf{H} - \mathbf{I}]\mathbf{x}(kT) + \mathbf{c}^T\mathbf{L}\,\mathbf{z}(kT) = \mathbf{c}^T\mathbf{D}\,\mathbf{x}(kT) + \mathbf{c}^T\mathbf{L}\,\mathbf{z}(kT) \qquad (9)$$

where:

$$\mathbf{D} = \begin{bmatrix} \mathbf{d_{q_1}} & \mathbf{d_{q_2}} \end{bmatrix} \qquad (10)$$

$$\mathbf{d_{q_1}} = \begin{bmatrix} A\Omega j + \sum_{i=2}^{3} a_i w^{(i-1)} + B\sum_{i=2}^{3} a_i w^{(i-2)} - 1 \\ A\Omega w - a_1 w^{(1)} - B a_1 w \end{bmatrix}, \ \mathbf{d_{q_2}} = \begin{bmatrix} w^{(1)} + wB \\ w^{(2)} + w^{(1)}B - 1 \end{bmatrix} \qquad (11)$$

$$\mathbf{L} = \begin{bmatrix} \mathbf{l_{q_1}} & \mathbf{l_{q_2}} \end{bmatrix}, \quad \mathbf{l_{q_1}} = \begin{bmatrix} l_{q_1}^1 \\ l_{q_1}^2 \end{bmatrix}, \quad \mathbf{l_{q_2}} = \begin{bmatrix} 0 \\ 0 \end{bmatrix},$$

$$l_{q_1}^1 = -(b_1 + b_2 A_{0,1})w + \Gamma(-\frac{b_1}{T_1} j - b_2 A_{1,1} w)\,,\ l_{q_1}^2 = -(b_1 + b_2 A_{0,1})w^{(1)} + \Gamma(-\frac{b_1}{T_1} w - b_2 A_{1,1} w^{(1)}) \qquad (12)$$

Starting from the general conditions (6), taking in account (9) and (10) of the zig-zag movement mode existence for the system analysed, the following relations are obtained:

$$[(\mathbf{c_q}\,\mathbf{d_{q_1}}) - c\,(\mathbf{c_q}\,\mathbf{d_{q_2}})]\,x_1(kT) \begin{cases} < 0 & for \quad g > 0 \\ > 0 & for \quad g < 0 \end{cases} \qquad (13)$$

$$\mathbf{c_q}\,\mathbf{l_{q_1}}\,z_1(kT) \quad \begin{cases} < 0 & za \quad g > 0 \\ > 0 & za \quad g < 0 \end{cases} \qquad (14)$$

where: $\mathbf{c_q} = \begin{bmatrix} c & 1 \end{bmatrix}$.

Replacing relations (11), expression (13) assumes the following form:

$$[\Omega(cAj + Aw) + (ca_2 - a_1 - c^2)w^{(1)} + B(ca_2 w - c^2 w - a_1 w)]x_1(kT) \begin{cases} > 0 \ for \ g > 0 \\ < 0 \ for \ g < 0 \end{cases} \qquad (15)$$

Taking into consideration relation (4), expression (15) can be written in the form:

$$\omega_1 \geq \max_{a_1, a_1, b_2} \frac{(-ca_2 + c^2 - a_1)\,w^{(1)} - B\,(ca_2 w - c^2 w - a_1 w)}{A(w + cj)} \qquad (16)$$

$$\lambda_1 \leq \min_{a_1, a_2, b_2} \frac{(-ca_2 + c^2 - a_1)\,w^{(1)} - B\,(ca_2 w - c^2 w - a_1 w)}{A(w + cj)} \qquad (17)$$

Replacing relations (12), expression (14) assumes the following form:

$$(c\,l_{q_1}^1 + l_{q_1}^2)\,z_1(kT) \quad \begin{cases} > 0 & for \quad g > 0 \\ < 0 & for \quad g < 0 \end{cases} \qquad (18)$$

Taking into consideration relation (4), expression (18) can be written in the form:

$$\gamma_1 \geq \max_{b, b_2} \frac{(b_1 + b_2 A_{0,1})w^{(1)} + c(b_1 + b_2 A_{0,1})w}{-\frac{b_1}{T_1} w - b_2 A_{1,1} w^{(1)} + c(-\frac{b_1}{T_1} j - b_2 A_{1,1} w)} \qquad (19)$$

$$\gamma_1 \geq \max_{b, b_2} \frac{(b_1 + b_2 A_{0,1})w^{(1)} + c(b_1 + b_2 A_{0,1})w}{-\frac{b_1}{T_1} w - b_2 A_{1,1} w^{(1)} + c(-\frac{b_1}{T_1} j - b_2 A_{1,1} w)} \qquad (20)$$

For T=0, relations (16), (17), (19) and (20) should represent relations for the continuous-time VSS of the second order with finite zero. Taking into consideration that $w^{(1)}(0) = w(0) = j(0) = 0$ *expressions (16), (17), (19) and (20) are indefinite (indefiniteness of the 0/0 type). Differentiating the numerator and the denominator as well as taking into consideration that* $w^{(2)} = 1$, *expressions (16), (17), (19) and (20) are reduced to the known existence conditions of the sliding mode for the continuous-time VSS of the second order with finite zero [16]:*

$$\omega_1 \geq \max_{a, a_2, b_2} \frac{ca_2 - a_1 - c^2}{b_2 A_{1,1}}, \quad \omega_1 \geq \max_{a, a_2, b_2} \frac{ca_2 - a_1 - c^2}{b_2 A_{1,1}}\ ,\ \gamma_1 \geq \max_{b_1, b_2} \frac{-b_1 - b_2 A_{0,1}}{b_2 A_{1,1}},\ \ \gamma_2 \leq \min_{b_1, b_2} \frac{-b_1 - b_2 A_{0,1}}{b_2 A_{1,1}}\ .$$

The implemented discrete-time VSS controller makes the high quality process regulation possible which is reflected in: monotonous aperiodic regulation process, high speed performance and system movement invariance at the final phase of regulation from the plant parameters change over the wide range.

In the given class of VSS controller with quasi-relay control a steady-state error may be occur if the system is of the zero type. This is consequence of the sliding mode loses in vicinity of equilibrium. The steady-state error signal in the considered class of control systems may be determined using classical relation:

$$x_1(\infty) = \lim_{s\to 0} s\, X_1(s) = \frac{r_0}{1+K_p},$$

$$K_p = \lim_{s\to 0} W_p(s) = \lim_{s\to 0} \frac{\Psi\, W(s)}{1+\Phi + s\,T_1} = \frac{\omega_1\, b_1}{(1+\gamma_1)\, a_1}.$$

where r_0 *- is constant reference input signal.*

This error can be decreased by increasing the values of parameters ω_1, ω_2 *and* c *of the discrete-time VSS controller, but this conditions occurrence of a higher overshoot during the process regulation, which can be decreased by decreasing the sampling period. Thus, optimum selection of parameters of the discrete-time VSS controller can result in a compromise between the steady-state error value and the overshoot. If the control plant is of zero type, the steady-state zero error at the given constant input may be accomplished by introducing integration in the control signal action. In the practice of discrete-time control systems the approach is in use by introducing the PI control action into the main feedback loop (Figure 1).*

ILLUSTRATIVE EXAMPLE

For the purpose of verifying the relations obtained for the discrete-time VSS regulator synthesis, a digital regulation of a dc motor rotor current was simulated. A dc motor of the following characteristics was taken as an example:

$$K_y = 0.33\,Vs/rad, \quad T_{meh} = 27.1\,ms,$$
$$K_t = 0.33\,Nm/rad, \quad T_{el} = 3.4\,ms$$
$$0.711\,Nm \le J \ge 1.422\,Nm,$$
$$0.00025\,Nms/rad \le F \ge 0.001\,Nms/rad,$$
$$L_r = 14.3\,mH, \quad R_r = 4.2\,\Omega.$$

Starting from the basic relations for the dc motor, the following transfer function is obtained:

$$W(s) = \frac{I_R(s)}{U_R(s)} = \frac{(T_{meh}/R)s + (T_{meh}/R)(F/J)}{T_{meh}T_{el}\,s^2 + (T_{meh} + T_{meh}T_{el}\,F/J)s + 1} = \frac{0.711s + 0.5}{0.01s^2 + 2.993s + 111}$$

If discretization of the sampling period T=5ms was introduced and the finite zero influence eliminated by introduced time-constant filter $T_1 = 1.51\,s$*, the following parameters values can be selected for the implementation of the discrete control system:*

- *for the system without PI action:* $\omega_1 = 500, \quad \lambda_1 = -500, \quad \gamma_1 = 0.02,$
  $\mu_1 = -0.02 \quad i \quad c = 341,$
- *for the system with PI action:* $\omega_1 = 500, \quad \lambda_1 = -500, \quad \gamma_1 = 0.02,$
  $\mu_1 = -0.02 \quad i \quad c = 341,$

The simulation results are presented in the form of the output step response (Figures 3 and 4). The output variable diagrams in Figures 3 and 4 that by introducing the PI control action into the main feedback loop have not steady-state error. The switches in quasi-sliding mode are not visible, because the choice of parameters provides monotonuous aperiodic regulation process. But in actual conditions will appear the switches.

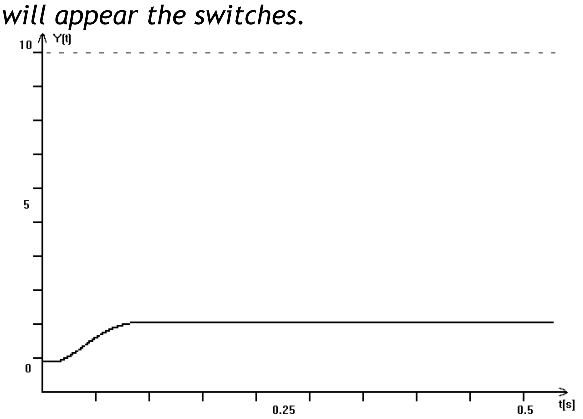

Figure 3. Output variable diagram for the system without the PI control action

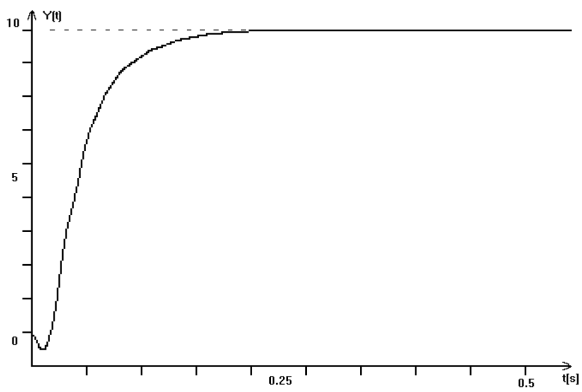

Figure 4. Output variable diagram for the system with the PI control action

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CONCLUSIONS

Analyzed in the paper are conditions to achieve the desired character of behavior and accuracy of operation in the steady-state and transitional mode of discrete-time VSS when regulating the plant with finite zeros. An illustrative example is used to show the synthesis procedure of the discrete-time VSS regulator with PI control action compensator. Based on a test, it can be concluded that the proposed mode of control is possible and that it yields good results as well as that the discrete-time VSS characteristics are better than those of a conventional system. The only disadvantage of the discussed method is that the finite plant zeroes can not be non-minimum phase.

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