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Analysis and calculation of the dynamic voltage reserve of the converter when working under load in systems of subject regulation by electric drives of direct current

***Abstract**. The article presents the calculation of the voltage reserve of the converter, which feeds the DC electric motor, in static and astatic systems of subordinate regulation under various forms of disturbing influence. The results of the calculations, based on the analytical method, make it possible to understand more deeply the nature of the dependence of the instantaneous and maximum values of the curves describing the voltage of the converter on the time constants of the systems, to determine their extreme values and to indicate ways of reducing the voltage reserve. The given examples show a significant dependence of the amount of the voltage reserve of the converter on the form of the disturbing influence.*

***Streszczenie**. W artykule przedstawiono obliczenia rezerwy napięciowej przetwornicy zasilającej silnik elektryczny prądu stałego, w statycznych i astatycznych układach regulacji podrzędnej pod wpływem różnych form wpływów zakłócających. Wyniki obliczeń, opartych na metodzie analitycznej, pozwalają głębiej zrozumieć naturę zależności wartości chwilowych i maksymalnych krzywych opisujących napięcie przetwornicy od stałych czasowych układów, wyznaczyć ich wartości skrajnych oraz wskazanie sposobów zmniejszenia rezerwy napięciowej. Podane przykłady pokazują znaczną zależność wielkości rezerwy napięciowej przekształtnika od postaci oddziaływania zakłócającego. (**Analiza i obliczenie dynamicznej rezerwy napięciowej przekształtnika podczas pracy pod obciążeniem w układach przedmiotowej regulacji za pomocą napędów elektrycznych prądu stałego**)*

Key words: static and astatic systems, dynamic voltage reserve, transfer and transition functions, extremum.
Słowa kluczowe: static and astatic systems, dynamic voltage reserve, transfer and transition functions, extremum.

Formulation of the problem

A large number of works [1-5] are devoted to the study of transient processes in systems of subordinate speed control of a direct current motor. Basically, these studies are related to the formation of technically optimal transient curves of armature current and speed. However, in order to form them, it is necessary to ensure the necessary power of the converter, that is, to choose a converter taking into account the necessary voltage reserve [2, 6-11]. In-depth research in this direction is insufficient. The main task of this work is to try to eliminate methodological problems related to the selection of the voltage of the converter.

Research tasks

I. Static regulation system.

a) single disturbing influence:

- make the transfer function of the voltage of the converter;
- calculate the transient function of the voltage of the converter;
- plot the curves of transient processes of the converter voltage at different values of the time constants of the electric drive system and analyze the dependence of the converter voltage reserve on them.

b.) linearly increasing with a limit disturbing influence:

- make the transfer function of the voltage of the converter;
- calculate the transient function of the voltage of the converter;
- plot the curves of transient processes of the converter voltage at different values of the time constants of the electric drive system and analyze the dependence of the converter voltage reserve on them.

II. Astatic control system.

a) single disturbing influence:

- make the transfer function of the voltage of the converter;
- calculate the transient function of the voltage of the converter;
- plot the curves of transient processes of the converter voltage at different values of the time constants of the electric drive system and analyze the dependence of the converter voltage reserve on them.

b) linearly increasing with a limit disturbing influence:

- make the transfer function of the voltage of the converter;
- calculate the transient function of the voltage of the converter;
- plot the curves of transient processes of the converter voltage at different values of the time constants of the electric drive system and analyze the dependence of the converter voltage reserve on them.

I. Control system with a proportional speed controller

Sufficient dynamic reserve voltage of the converter is one of the conditions for realizing the specified speed in the system of subordinate motor speed control [3, 12-15]. This article provides a method for calculating the dynamic margin of the converter voltage for a two-loop regulation system (Fig. 1) when adjusting the regulation loops according to the modular optimum. Compensation for the effect of the motor EMF on the current circuit is assumed [4, 16].

The analysis will be carried out under the following assumptions:

- the current of the armature circuit is continuous and the external characteristic of the converter does not have breaks at low currents;
- the armature reaction flux is not taken into account;
- the effect of filters in feedback circuits for current and motor speed is not taken into account.

Below we consider issues related to the study of the behavior of the increase in the voltage of the converter when a disturbing influence is applied, which has the form of either a single jump, or - linearly variable with a limit [6, 17-19].

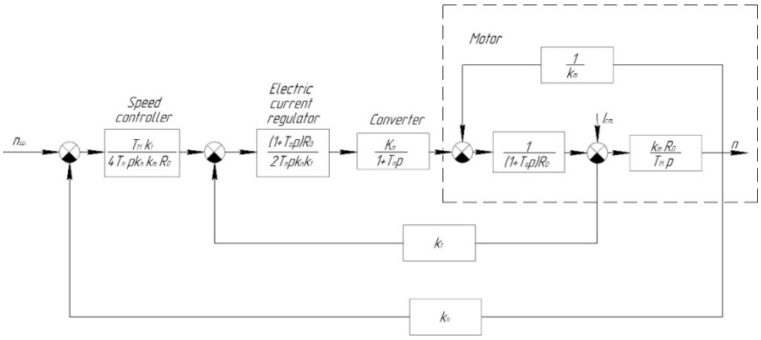

Fig.1. Static system of subordinate regulation by a direct current electric motor: Tм, Ta, Tn – time constants, respectively, electromechanical, electromagnetic armature circuit and small uncompensated current circuit; Ro – armature resistance; coefficients k_m, k_t, k_n – respectively, feedback on the speed, on the armature current, the gain of the converter; k=1/(Ce·Φ); Ce – coefficient of the machine; Φ – excitation magnetic flux

a) Single disturbing influence

The transfer function connecting the armature current i(t) with the static current Ic has the following form [3, 20]:

$$\frac{iR_o}{I_cR_o}(q)=\frac{1}{\frac{1}{8}\cdot q^3+\frac{1}{2}\cdot q^2+q+1}=\frac{1}{N_3(q)} \quad (1)$$

where $q=4T_пp$ – normalized parameter.

The corresponding transfer function (1) transition function for the armature current will be equal to [21]:

$$\frac{iR_o}{I_cR_o}(\tau)=1-e^{-2\tau}-\frac{2}{\sqrt{3}}e^{-\tau}\sin\sqrt{3}\,\tau \quad (2)$$

where $\tau=\frac{t}{4T_П}$ relative time, t – absolute time.

Increasing the voltage of the converter $\Delta U_{пр}$ can be determined by such a dependence:

$$\frac{\Delta U_{np}}{I_cR_o}(q)=\frac{\Delta U_a}{I_cR_o}(q)-\frac{\Delta e_m}{I_cR_o}(q) \quad (3)$$

where ΔU_a., Δe_m – increase in armature voltage and electric driving force of the motor.

Transfer function conversion (3):

$$\frac{\Delta U_{np}}{I_cR_o}(q)=\frac{1}{N_3(q)}+\frac{T_a}{4T_n}\cdot\frac{q}{N_3(q)}-\frac{4T_n}{T_м}\cdot\frac{N_2(q)}{N_3(q)} \quad (4)$$

where $\frac{1}{N_3(q)}=\frac{iR_o}{I_cR_o}(q)$; $\frac{1}{N_2(q)}=\frac{1}{\frac{1}{8}q^2+\frac{1}{2}q+1}$.

Given that the transfer function $\frac{q}{N_3(q)}$ corresponds to the transfer function [9] $2\left\{e^{-2\tau}+e^{-\tau}\left[\frac{1}{\sqrt{3}}\sin\sqrt{3}\,\tau-\cos\sqrt{3}\,\tau\right]\right\}$, and the transfer function $\frac{N_2(q)}{N_3(q)}$ corresponds to the transition function [7] $1-\frac{1}{2}e^{-2\tau}-\frac{1}{2}e^{-\tau}\left[\cos\sqrt{3}\,\tau+\frac{1}{\sqrt{3}}\sin\sqrt{3}\,\tau\right]$, the transient function of the voltage increase of the converter can be replaced by the following form:

$$\frac{\Delta U_{np}}{I_cR_o}(\tau)=1-A+\left(2B+\frac{1}{2}A-1\right)e^{-2\tau}+\left[\left(\frac{1}{2}A-2B\right)\cos\sqrt{3}\,\tau+\frac{1}{\sqrt{3}}\left(2B+\frac{1}{2}A-2\right)\sin\sqrt{3}\,\tau\right]e^{-\tau} \quad (5)$$

where $A=\frac{4T_n}{T_M}$; $B=\frac{T_a}{4T_n}$.

Fig. 2 shows the curves of instantaneous values (solid lines) for A=0.9; B=0...3 constructed according to equation (5). The presence of a negative section of the voltage increase of the converter (V=0...2) characterizes the degree of influence of positive feedback on the EMF of the motor at a given speed of the current circuit. As this influence decreases, the negative section of the voltage increase of the converter disappears (B>3; A=0.9). The point "a" of the intersection of the curves of instantaneous values $\frac{\Delta U_{Пр}}{I_cR_o}(\tau)$ determines the time when the armature current reaches its maximum value ($\tau_m=2{,}42$), which depends only on the speed of the control system [22, 23]. At this point, the instantaneous value does not depend on the time constant Tya and approximately determines the static state of the system. The same figure shows a family of curves (dashed lines) for the case B=1.5; A=0.45; 0.9; 1.35, constructed according to equation (5). The fact that the curves do not intersect shows that the time of the maximum dynamic drop in speed changes as a function of the parameter A with an unchanged value of B.

To determine the dynamic reserve voltage of the converter, it is necessary to take the derivative of (5) and equate it to zero.

$$\left(\frac{\Delta U_{np}}{I_cR_o}\right)'(\tau)=2\left(1-2B-\frac{1}{2}A\right)e^{-2\tau}+\left[\begin{matrix}(4B-2)\cos\sqrt{3}\,\tau-\\ \frac{1}{\sqrt{3}}(8B+11A-2)\sin\sqrt{3}\,\tau\end{matrix}\right]e^{-\tau}=0 \quad (6)$$

Determination of the maximum value of the function (5) $\frac{\Delta U_{Пр.max}}{I_cR_o}$ carried out on a computer at the moment of time τ=τмах, obtained with (6) and substitution $\tau_{мах}$ in equation (5). The results of the calculations are shown in (Fig. 3). The dynamic reserve voltage of the converter for B>1 lines increases when A=const. In the V<0.8 zone, the dynamic reserve voltage of the converter is a non-linear function. Based on the curves of Fig. 3 the function approximation equation is obtained $\frac{\Delta U_{Пр.max}}{I_cR_o}=f(A,B)$ on a linear section in the range of values 0.8<B<5 and in the range of values 0<A<4.95, which has the form:

$$\frac{\Delta U_{Пр.мах}}{I_cR_o}=0{,}5-0{,}89A+0{,}81B. \quad (7)$$

From the analysis of the curves (Fig. 3) it follows that with an unchanged value of the time constant $T_a\geq 0{,}04\,s$ with decreasing time constant T_M the voltage margin increases linearly. Selection of minimum stock $\frac{\Delta U_{Пр.max}}{I_cR_o}=f(A,B)$ you can at $T_a\leq 0{,}04\,s$. Area of minimum values $\frac{\Delta U_{Пр.max}}{I_cR_o}=f(A,B)$ bounded by the dashed curve.

The zone of values of coefficient A limits the area of positive values of the function $\frac{\Delta U_{Пр.max}}{I_cR_o}=f(A,B)$ So, for example, V = 5 at all values 0 < A < 4.95, a dynamic margin of voltage of the converter is required.

b) Perturbation in the form of a linear signal with a limit.

During rolling, as shown in a number of works [24, 25] and in particular in the laboratory studies of the authors, the static moment is not applied to the motor shaft in jumps but has the form of a linear signal with a limit. The rise time of the rolling moment depends on the gripping condition and, without taking into account slippage, is about 0.3 sec., for the rolling condition of the blooming type [24]. The nature of the static moment change is determined by the rigidity of the cage and spindle. Below, the behavior of the change in the voltage of the converter when the static moment changes is considered according to the linear law with a limit, and the stiffness of the cage and spindles is not taken into account. Knowing the rate of growth of the static load, it is possible to reduce the dynamic voltage reserve of the converter in comparison with the case of a single application of the load.

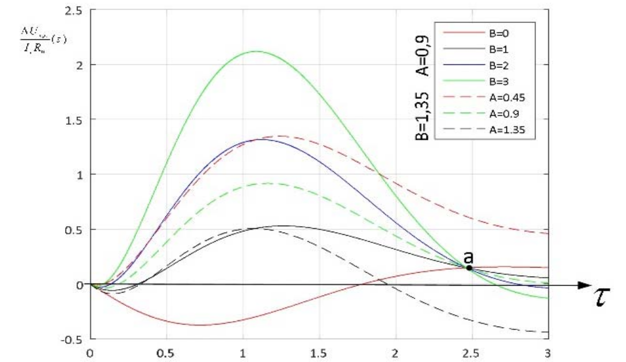

Fig. 2. Curves of instantaneous values of the function $\frac{\Delta U_{\Pi p}}{I_c R_o}(\tau)$ at different values of coefficients A and B in a static engine speed control system and a single disturbing influence, m=2.

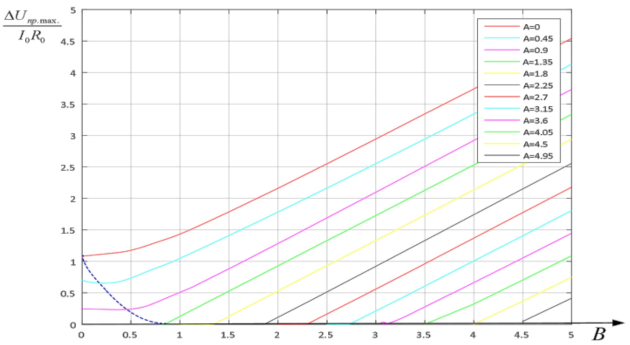

Fig. 3. Curves of maximum function values $\frac{\Delta U_{\Pi p max c}}{I_c R_o} = f(A, B)$ at different values of coefficients A and in a static engine speed control system and a single disturbance, m=2.

Suppose that the load grows linearly up to the time limit τu, then the behavior of the armature current in this area can be determined by integrating the transient function of the armature current (2) under a single disturbance.

In this case, the transient function of the armature current in the time section $\tau \leqslant \tau_u$ will look like this:

$$\frac{\iota R_o}{I_c R_o}(\tau) = \frac{1}{\tau_u}\left[\tau - 1 + \frac{1}{2}e^{-2\tau} + \frac{1}{2}e^{-\tau}\left(\cos\sqrt{3}\,\tau + \frac{1}{\sqrt{3}}\sin\sqrt{3}\,\tau\right)\right] \tag{8}$$

where $\tau_u = \frac{t_u}{4T_n}$ - relative load growth time; t_u – absolute load rise time.

Similarly to the previous explanations, we obtain the transient function of the voltage increase of the converter in the time section $\tau \leqslant \tau_u$:

$$\frac{\Delta U_{np1}}{I_c R_o}(\tau) = \frac{1}{\tau_u}\left\{\begin{aligned}&\left(B + \frac{1}{2}A - 1\right) + \tau(1 - A) + \left(\frac{1}{2} - B - \frac{1}{4}A\right)e^{-2\tau} + \\ &+\left[\begin{aligned}&\left(\frac{1}{2} - \frac{1}{4}A\right)\cos\sqrt{3}\,\tau + \\ &\frac{1}{\sqrt{3}}\left(\frac{1}{2} - 2B - \frac{1}{4}A\right)\sin\sqrt{3}\,\tau\end{aligned}\right]e^{-\tau}\end{aligned}\right\} \tag{9}$$

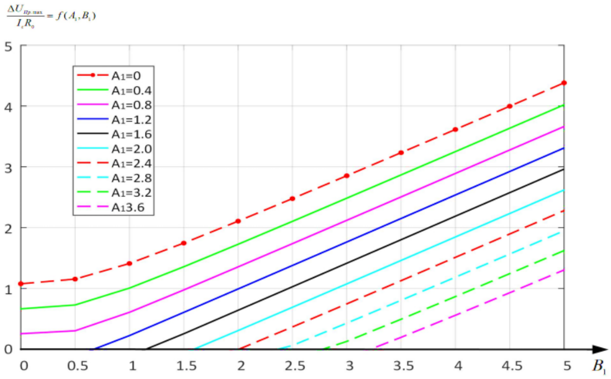

Fig. 4. Curves of maximum function values $\frac{\Delta U_{\Pi p.max}}{I_c R_o}$ at different values of coefficients A and B in the static engine speed control system and linearly increasing perturbed at τ_u=0.625 and m=2.

Transient function for the voltage gain of the converter after the cut-off in the time section $\tau \geqslant \tau_u$:

$$\frac{\Delta U_{np.2}}{I_c R_o}(\tau) = 1 - A + F(\tau) - F(\tau - \tau_u) \tag{10}$$

where

$$F(\tau) = \frac{1}{\tau_u}\left\{\begin{aligned}&-\frac{1}{2}\left(-1 + 2B + \frac{1}{2}A\right)e^{-2\tau} + \\ &\left[\begin{aligned}&\left(\frac{1}{2} - \frac{1}{4}A\right)\cos\sqrt{3}\,\tau + \\ &+\frac{1}{\sqrt{3}}\left(\frac{1}{2} - 2B + \frac{1}{4}A\right)\sin\sqrt{3}\,\tau\end{aligned}\right]e^{-\tau}\end{aligned}\right\};$$

F(τ-τ$_u$) – similar function *F(τ)*, but shifted in time to τ_u.

To determine the dynamic reserve voltage of the converter $\frac{\Delta U_{\Pi p.max}}{I_c R_o}$ differentiate (9) i (10), and we equate the result to zero. For a period of time $\tau \leqslant \tau_u$:

$$\frac{\Delta U'_{np1}}{I_c R_o}(\tau) = \frac{1}{\tau_u}\left\{\begin{aligned}&1 - A - \left(1 - 2B - \frac{1}{2}A\right)e^{-2\tau} + \\ &+\left[\begin{aligned}&\left(-2B + \frac{1}{2}A\right)\cos\sqrt{3}\,\tau + \\ &\frac{1}{\sqrt{3}}\left(-2 + 2B + \frac{3}{2}A\right)\sin\sqrt{3}\,\tau\end{aligned}\right]e^{-\tau}\end{aligned}\right\} = 0 \tag{11}$$

For a period of time $\tau \geqslant \tau_u$:

$$\frac{\Delta U'_{np.2}}{I_c R_o}(\tau) = F'(\tau) - F'(\tau - \tau_u) = 0 \tag{12}$$

where

$$F'(\tau) = \frac{1}{\tau_u}\left\{\begin{aligned}&\left(1 - 2B - \frac{1}{2}A\right)e^{-2\tau} \\ &+\left[\begin{aligned}&\left(-2 + \frac{1}{2}A\right)\cos\sqrt{3}\,\tau + \\ &+\frac{1}{\sqrt{3}}\left(-2 + 2B - \frac{3}{2}A\right)\sin\sqrt{3}\,\tau\end{aligned}\right]e^{-\tau}\end{aligned}\right\}$$

F´(τ⩾τ$_u$) – similar function *F´(τ)*, but shifted in time to τ_u.

The determination of the maximum value of functions (9) and (10) was carried out on a value calculator $\tau = \tau_{Max}$, obtained from (11) and (12) and substitution τ_{Max}, respectively, in equations (9) and (10). As can be seen from the calculation results, the function $\frac{\Delta U_{\Pi p.max}}{I_c R_o} = f(A, B)$ at τ_u=const and at B>0,5 straight line. On the basis of these calculations, the approximation equations of the function were obtained $\frac{\Delta U_{\Pi p.max}}{I_c R_o} = f(A, B)$ for 0.5<B<10.

These equations are presented in Table 1.

Table 1. The approximation equation of the function $\frac{\Delta U_{\Pi p.max}}{I_c R_o} = f(A, B)$ in a static system with a linearly growing disturbance

№	Value τ_u	Zone of values A	Equation
1	5/4	0<A<6,60	0,60-1,11A+0,67B
2	10/4	0<A<6,31	0,68-0,80A+0,424B
3	15/4	0<A<3,80	0,82-0,89A+0,258B
4	20/4	0<A<2,85	0,86-0,98A+0,196B
5	25/	0<A<2,50	0,88-0,98A+0,158B

Based on the curves fig. 4 and table 1 can be determined dynamic margin of voltage of the converter. Given the value of τu, it is possible to determine at which values of A and B the dynamic reserve of the converter is required. For example, when τ_u =5/4; B=5

$$\frac{\Delta U_{\Pi p.max}}{I_c R_o} = 0{,}6 - 1{,}11A + 0{,}67 \cdot 5 = 0{,}6 - 1{,}11A + 3{,}95 = = -1{,}11A + 3{,}55 = 0.$$

Then, for all values 0<A<3.2, a dynamic voltage reserve of the converter is required. A comparison with the case of a single disturbance (7) shows a significant narrowing of the definition area of the minimum dynamic margin of the converter voltage and, therefore, a reduction in the pre-regulation of the armature current, which allows better use of the motor from an overload in the case of a linear one with a limitation of the disturbance signal.

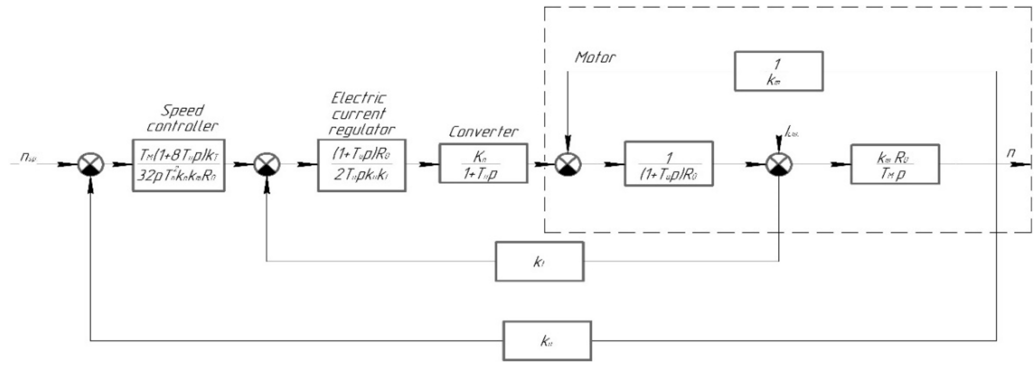

Fig. 5. Astatic system of subordinate regulation of a direct current electric motor

II. Control system with proportional-integral speed controller

Let's consider the method of calculating the dynamic margin of the converter voltage for a two-loop control system (Fig. 5) with a symmetrical setting of the speed controller when applying a disturbing in-fluence that has the form of either a single jump or linearly increasing with a limit [3, 4, 26].

a) Single disturbing influence

The transfer function connecting the armature current i(t) with the static current Ic has the following form [2]:

$$\frac{iR_o}{I_c R_o}(q) = \frac{q+1}{\frac{q^4}{64} + \frac{q^3}{8} + \frac{q^2}{2} q + 1} \tag{13}$$

where $q = 8T_n p$ - normalized parameter;

The corresponding transition function of the transfer function (13) for the armature current will be equal to [6]:

$$\frac{iR_o}{I_c R_o}(\tau) = 1 - e^{-2\tau}[(1+6\tau)\cos 2\tau + 2(\tau - 1)\sin 2\tau] \tag{14}$$

where $\tau = \frac{t}{8T_\Pi}$ relative time, t – is absolute time.

Voltage gain of the converter $\Delta U_{пр}$ can be determined by such a dependence:

$$\frac{\Delta U_{np}}{I_c R_o}(q) = \frac{\Delta U_a}{I_c R_o}(q) - \frac{\Delta e_m}{I_c R_o}(q) \tag{15}$$

where ΔU_a., Δe_m – accordingly, the increase in armature voltage and E.M.P. engine.

After converting which we will get the function:

$$\frac{\Delta U_{np}}{I_c R_o}(q) = \frac{q+1}{N_4(q)} + \frac{T_a}{8T_n} \cdot \frac{q(q+1)}{N_4(q)} - \frac{4T_n}{T_м} q \cdot \frac{N_2(q)}{N_4(q)} \tag{16}$$

where $\frac{q+1}{N_4(q)} = \frac{iR_o}{I_c R_o}(q)$; $\frac{1}{N_2(q)} = \frac{1}{\frac{q^2}{32} + \frac{q}{4} + 1}$.

Since the transfer function $\frac{q(q+1)}{N_4(q)}$ corresponds to the transition function: $e^{-2\tau}[4\tau \cos 2\tau + 2(4\tau - 1)\sin 2\tau]$, and the transfer function $\frac{qN_2(q)}{N_4(q)}$ corresponds to the transition function $\frac{1}{2}\left[-2\tau \cos 2\tau + \left(\frac{3}{2} + \tau\right)\sin 2\tau\right] e^{-2\tau}$, then the transient function of the voltage increase of the converter can be written in the following form:

$$\frac{\Delta U_{np}}{I_c R_o}(\tau) = 1 + e^{-2\tau}\left\{\begin{matrix}[-1 + 2\tau(-3 + 4B_1 + A_1)]\cos 2\tau + \\ +[(2 - 4B_1 - 1{,}5A_1) + 2\tau(-1 + 8B_1 - 0{,}5A_1)]\sin 2\tau\end{matrix}\right\}, \tag{17}$$

where $A_1 = \frac{8T_\Pi}{T_m}$; $B_1 = \frac{T_a}{8T_\Pi}$.

Figure 6 shows the curves of instantaneous values of the function $\frac{\Delta U_{\Pi p}}{I_c R_o}(\tau)$ for a separate case (solid lines) A1=2.0; B1=0...0.75, constructed according to equation (17). Let's analyze these curves. The presence of a negative part of the increase of the converter (B1=0...0.5) characterizes the degree of influence of positive feedback on the EMF of the motor at a given speed of the current circuit. As the degree of EMF influence decreases, the negative part of the converter voltage increase disappears (B1>0.75; A1=2.0).

Point a1 of intersection of the curves of instantaneous values $\frac{\Delta U_{\Pi p}}{I_c R_o}(\tau)$ determines the time for the armature current to reach its maximum value, which depends only on the speed of the regulation system. At this point, at a specific value of V, the voltage increase is minimal, and at the maximum voltage increase, it coincides in phase with the maximum value of the armature current. The same figure shows a family of curves $\frac{\Delta U_{\Pi p}}{I_c R_o}(\tau)$ (dashed lines) for the case B1=0.3125 and A1=2.4...7.2, built according to the equation (17).

Point a2 of intersection of the curves of instantaneous values $\frac{\Delta U_{\Pi p}}{I_c R_o}(\tau)$ determines the time of the maximum dynamic drop in engine speed. At this point, the instantaneous value of the voltage increase of the converter does not depend on the electromechanical time constant of the drive. The analysis of the curves in Fig. 6

shows that up to a certain value of B1 at a given A1, the function (16) has a minimum (for example, at B1⩾0.5). To determine the maximum value of function (17), i.e., the dynamic margin of the converter voltage, we take its derivative and, having set it equal to zero, we obtain:

(18) $$\frac{\Delta U^{'}_{np}}{I_c R_o}(\tau) = \begin{Bmatrix} [-A_1 + 4\tau(2 + 4B_1 - 1{,}5A_1)] \cos 2\tau + \\ +2\begin{bmatrix} (-2 + 12B_1 + A_1) - \\ -2\tau(-4 + 12B_1 + 0{,}5A_1) \end{bmatrix} \sin 2\tau \end{Bmatrix} e^{-2\tau} = 0$$

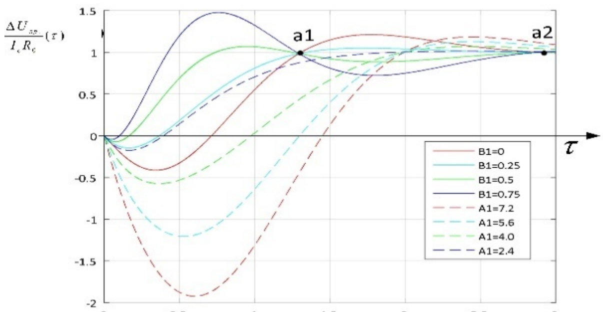

Fig. 6. Curves of instantaneous values of the function $\frac{\Delta U_{Пр}}{I_c R_o}(\tau)$ in an astatic system of subordinate engine speed regulation at different values of coefficients A1 and B1 and a unit disturbance.

The determination of the maximum value of function (17) was carried out according to the method described in [18] with the value τ=τmax obtained from (18) and substituting τmax into equation (17). The results of the calculations are shown in (Fig. 7), on which two characteristic regions, separated by a dashed line, can be distinguished for small values of B1, where with the decrease of A1, the value $\frac{\Delta U_{Пpmax}}{I_c R_o}$ first falls, and then the region of relatively large values of B1 increases, where with the decrease of A1 the value $\frac{\Delta U_{Пp.max}}{I_c R_o}$ continuously growing. At the border of the regions there are points of minimum voltage reserve of the converter. At a given speed of the optimal structure of the engine speed control system, the minimum dynamic margin of the converter voltage can be obtained in two ways: either by changing the engine design, or by changing the converter circuit, that is, the problem arises of obtaining such anchor and electromechanical time constants that would correspond to the minimum dynamic voltage margin of the converter. Based on the curves (Fig. 7), the function approximation equation was obtained $\frac{U_{Пpmax}}{I_c R_o} = f(A, B)$ on a linear section (table 2).

Table 2. The approximation equation of the function $\frac{\Delta U_{Пp.max}}{I_c R_o} = f(A, B)$ in a static system with a single perturbation

Zone of values A_1	Zone of values B_1	Analytical expression $\frac{U_{Пp.max}}{I_c R_o} = f(A, B)$
0<A1<6,0	0,75<B1<1,25	0,95+1,96B-0,475A

Based on the data of fig. 7 starting with curves $A_1 = 2{,}4 \div 3{,}6$ on some segments of the value of the function $\frac{U_{Пp.max}}{I_c R_o} = f(A, B) \approx 1$ will illustrate a straight parallel parameter B_1.

b) Perturbation in the form of a linear signal with a limit.

As mentioned above, accounting for this type of disturbance allows to reduce the dynamic voltage reserve. Consider this provision for an astatic control system.

Suppose that the load grows linearly up to the limit for a certain time τu, then the behavior of the armature current in this section can be determined by integrating the transient function of the armature current under a single disturbance, which has the following form in the section τ<τu:

(19) $$\frac{\iota R_o}{I_c R_o}(\tau) = \frac{1}{\tau_u}\left\{\tau - e^{-2\tau}\left[\left(\frac{3}{2} + \tau\right) \sin 2\tau - 2\cos 2\tau\right]\right\}.$$

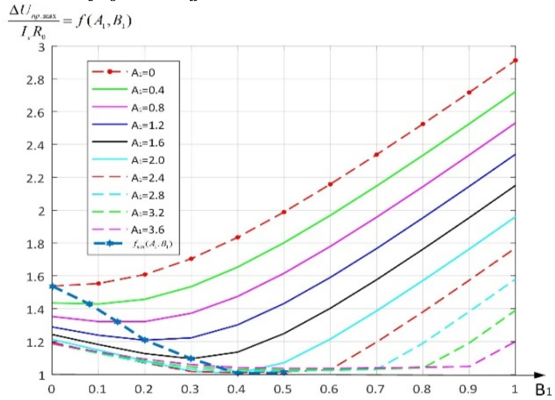

Fig. 7. Curves of maximum function values $\frac{\Delta U_{Пp.max}}{I_c R_o}$ in an astatic engine speed control system at different values of coefficients A1 and B1 and single disturbance, m=2.

Analogously to the previous explanations, we obtain the transient function of the voltage increase of the converter in the time section τ⩽τu:

(20) $$\frac{\Delta U_{np1}}{I_c R_o}(\tau) = \frac{1}{\tau_u}\left\{\left(B_1 - \frac{A_1}{2}\right) + \tau + \begin{Bmatrix} \left[\left(\frac{5}{8}A_1 + 2B_1 - \frac{3}{2}\right) - \tau\left(-\frac{3}{4}A_1 + B_1 + 1\right)\right] \times \\ \times \sin 2\tau + \begin{bmatrix} \left(-B_1 + \frac{A_1}{2}\right) + \\ \tau\left(-\frac{A_1}{4} - 6B_1 + 2\right) \end{bmatrix} \cos 2\tau \end{Bmatrix} e^{-2\tau}\right\}$$

Transient function of the voltage increase of the converter after cut-off in the time section τ⩾τu:

(21) $$\frac{\Delta U_{np.2}}{I_c R_o}(\tau) = 1 + F(\tau) - F(\tau - \tau_u)$$

where

$$F(\tau) = \frac{1}{\tau_u}\begin{Bmatrix} \left[\left(\frac{5}{8}A_1 + 2B_1 - \frac{3}{2}\right) - \tau\left(-\frac{3}{4}A_1 + B_1 + 1\right)\right] \times \\ \times \sin 2\tau + \left[\left(-B_1 + \frac{A_1}{2}\right) + \tau\left(-\frac{A_1}{4} - 6B_1 + 2\right)\right] \cos 2\tau \end{Bmatrix} e^{-2\tau},$$

where *F(τ-τu)* similar to the function F(τ), but shifted in time by τ_u.

To determine the dynamic voltage margin $\frac{\Delta U_{Пp.max}}{I_c R_o}$ we differentiate the converter (20) and (21) and the result is set to zero. On the time section $\tau \leq \tau_u$.

(22) $$\frac{\Delta U^{'}_{np1}}{I_c R_o}(\tau) = \frac{1}{\tau_u}\left\{1 + \begin{Bmatrix} \left[\left(-\frac{3}{2}A_1 - 3B_1 + 2\right) + \tau(-A_1 + 14B_1 - 2)\right] \times \\ \times \sin 2\tau + [-1 + 2\tau(A_1 + 5B_1 - 3)] \cos 2\tau \end{Bmatrix} e^{-2\tau}\right\} = 0$$

For a period of time τ⩾τu

(23) $$\frac{\Delta U^{'}_{np.2}}{I_c R_o}(\tau) = F^{'}(\tau) - F^{'}(\tau - \tau_u) = 0$$

where

$$F^{'}(\tau) = \frac{1}{\tau_u}\begin{Bmatrix} \left[\left(-\frac{3}{2}A_1 - 3B_1 + 2\right) + \tau(-A_1 + 14B_1 - 2)\right] \times \\ \times \sin 2\tau + [-1 + 2\tau(A_1 + 5B_1 - 3)] \cos 2\tau \end{Bmatrix} e^{-2\tau};$$

where *F´(τ-τu)* - similar to the function F´(τ), but shifted in time by τ_u.

Determination of the maximum values of the functions for the values τ=τmax obtained from (22) and (23) and substituting τmax into equations (19) and (20). The calculation was carried out at τu=0.625; 1.25; 1,875; 2.5; 3,125. The corresponding values are summarized in Table 3. The analysis of the obtained curves shows that as τu increases, the $\frac{\Delta U_{Пp.max}}{I_c R_o}$ is falling. Compared to a single disturbance, this circumstance allows to reduce the necessary dynamic margin of voltage of the converter and to better use the motor on overload due to the reduction of the over-regulation of the armature current with a real disturbance signal.

As an example (Fig. 8), the approximated curves of the maximum values of the function are shown $f(A_1, B_1) = \frac{\Delta U_{\Pi p.max}}{I_o R_o}$ at τ=0,625. As in the case of a single disturbing effect of the curve in Fig. 8 divided by the function graph $f_{min}(A_1, B_1)$ into two regions. At the border of the regions there are points of minimum voltage reserve of the converter. For each value of τu, it is possible to determine the area with certain changes in the B1 parameter, where the function $\frac{\Delta U_{\Pi p.max}}{I_c R_o} \approx 1$, that is, this dependence will be illustrated by a line parallel to the axis of parameter B1. For example, τu=0.625; B1=0.325. Then, at all values of A1, a voltage margin of more than one is required, except for A1=2.4, where this margin is minimal. It is possible to determine with the values of τu at which values of A1 and B1 the necessary reserve voltage of the converter is required.

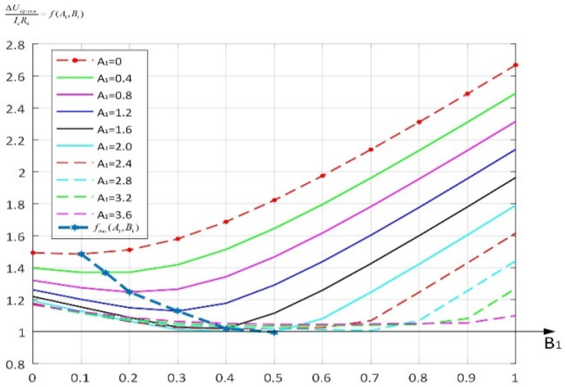

Fig. 8. Curves of maximum function values $\frac{\Delta U_{\Pi p.max}}{I_c R_o}$ in the astatic engine speed control system at different values of coefficients A1 and B1, τ_u=0.625 and m=2 with a linear limited excitation signal

Table 3. The approximation equation of the function $\frac{\Delta U_{\Pi p.max}}{I_c R_o} = f(A, B)$ in an astatic system in a linear system with a perturbed constraint

Values τ_u	Zone of values A_1	Zone of values B_1	Analytical expression $\frac{\Delta U_{\Pi p.max}}{I_c R_o} = f(A_1, B_1)$
0,625	$0<A_1<4,4$	$0,81<B_1<1,25$	$0,85+1,825B_1-0,325A_1$
1,250	$0<A_1<3,2$	$0,81<B_1<1,25$	$0,95+1,185B_1-0,375A_1$
1,875	$0<A_1<2,4$	$0,81<B_1<1,25$	$1,05+1,415B_1-0,275A_1$
2,5	$0<A_1<2,0$	$0,625<B_1<1,25$	$1,08+1,15B_1-0,175A_1$
3,125	$0<A_1<2, 0$	$0,56<B_1<1,25$	$1,06+1,09B_1-0,175A_1$

Conclusions

1. Analytical methods for calculating the converter voltage in compensated static and astatic engine speed control systems with variable ratios of equivalent time constants of control circuits have been developed, on the basis of which the dynamic margin of the converter voltage is selected.

2. It is shown that the dynamic voltage reserve of the converter depends on the form of the disturbing influence, which is determined by the technological process.

3. As the time τu increases, the maximum voltage reserve of the converter decreases.

4. The proposed formulas and tables for calculating the transformer's external reserve will allow for a rational choice of a power transformer.

5. Under other conditions, the voltage reserve of the converter for astatic systems is greater than in static systems.

6. The correct selection of the voltage supply of the converter helps to increase the efficiency of work, save electricity, electrical materials, non-ferrous and ferrous metals. The presented measures contribute to increasing the service life of the voltage converter, power transformer and electric motor.

7. The voltage converter, as an element of the subordinate regulation system, according to static and dynamic parameters, must be consistent with both the input parameter - the current regulator and the output parameter - the armature current of the main circuit motor.

8. Greater attention should be paid to the rational selection of the voltage reserve of the converter. With an overestimated voltage reserve of the converter, there is a need to increase the power of the power transformer, which leads to a deterioration of the power factor of the electrical installation.

9. An overestimated supply voltage of the converter negatively affects the insulation of the windings of the electric motor, increases the level of pulsations of the rectified voltage and current.

10. As the rate of change of the motor armature current increases, the voltage reserve of the converter should be greater. If the voltage reserve is selected too high, then the rate of change of the armature current of the electric motor must be limited (not to exceed the switching capacity of the motor).

11. With an undervoltage reserve of the converter, a failure may occur in the operation of the control system due to limited linearity of the converter characteristic and an uncontrolled decrease in speed, which occurs when the voltage of the electric motor is close to the nominal and full load.

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REFERENCES

[1]. Kondalkar V. V., Ryu G., Lee Y., Lee K. Development of highly sensitive and stable humidity sensor for real-time monitoring of dissolved moisture in transformer-insulating oil. *Sensors and Actuators B: Chemical*. 286 (2019), 377-385.

[2]. Razzaq A., Zainuddin H., Hanaffi F., Chyad R.M. Transformer oil diagnostic by using an optical fibre system: a review. *IET Science, Measurement & Technology*. 13 (2019). nr 5, 615-621.
[3]. Kupchuk I., Voznyak O., Burlaka S., Polievoda Yu., Vovk V., Telekalo N., Hontaruk Ya. Information transfer with adaptation to the parameters of the communication channel. *Przeglad elektrotechniczny*. 99 (2023). nr. 3, 194-199. https://doi.org/10.15199/48.2023.03.34
[4]. Tsurkan O., Kupchuk I., Polievoda Y., Wozniak O., Hontaruk Y., Prysiazhniuk Y. Digital processing of one-dimensional signals based on the median filtering algorithm. Przegląd elektrotechniczny. 98 (2022). nr. 11, 51-56. https://doi.org/10.15199/48.2022.11.08
[5]. Puyu V., Bakhmat M., Pantsyreva H., Khmelianchyshyn Y., Stepanchenko V., Bakhmat O. Social-and-Ecological Aspects of Forage Production Reform in Ukraine in the Early 21st Century. *European Journal of Sustainable Development*. 10 (2021). nr 1, 221–228.
[6]. Mazur V., Tkachuk O., Pantsyreva H., Demchuk O. Quality of pea seeds and agroecological condition of soil when using structured water. *Scientific Horizons*. 24 (2021). nr 7, 53-60.
[7]. Semenov, A., Osadchuk, O., Semenova, O., Voznyak, O., Rudyk, A., Koval, K. Research of dynamic processes in the deterministic chaos oscillator based on the colpitts scheme and optimization of its self-oscillatory system parameters. *Lecture Notes on Data Engineering and Communications Technologies*. 48 (2021). 181–205 http://dx.doi.org/10.1007/978-3-030-43070-2_10
[8]. Semenov, A.O., Voznyak, O.M., Osadchuk, O.V., Klimek, J., Orazalieva, S. Development of a non-standard system of microwave quadripoles parameters. *Proceedings of SPIE - The International Society for Optical Engineering*. 2019, 11176, 111765N http://dx.doi.org/10.1117/12.2536704
[9]. Hraniak V. F., Matviychuk V. A., Kupchuk I. M. Mathematical model and practical implementation of transformer oil humidity sensor. *Electronics*. 26 (2022). nr. 1, 3-8. https://doi.org/10.53314/ELS2226003H
[10]. Honcharuk I., Tokarchuk D., Gontaruk Y., Hreshchuk H. Bioenergy recycling of household solid waste as a direction for ensuring sustainable development of rural areas. *Polityka Energetyczna – Energy Policy Journal*, 26 (2023). nr 1, 23-42. https://doi.org/10.33223/epj/161467
[11]. Lohosha R., Prylutskyi A., Pronko L., Kolesnyk T. Organization of the System of Internal Marketing and Marketing of Interaction of Agricultural Enterprises for the Production of Biodiesel Based on Value Chain Analysis. *Journal of Environmental Management and Tourism,* 67 (2023), nr 3, 823-841. https://doi.org/10.14505/jemt.v14.3(67).21
[12]. Semenov, A., Semenova, O., Rudyk, A., Voznyak, O.,Pinaiev, B., Kulias, R. Mathematical Model of Microwave Devices on Resonant Tunneling Diodes for Practical Application in Radar and Electronic Systems. *2020 IEEE Ukrainian Microwave Week, UkrMW 2020 – Proceedings*. (2020). 272–277 https://doi.org/10.1109/UkrMW49653.2020.9252673
[13]. Hraniak V. F., Kukharchuk V. V., Bogachuk V. V., Vedmitskyi Y. G. at all. Phase noncontact method and procedure for measurement of axial displacement of electric machine’s rotor. *Proc. SPIE 10808, Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments 2018*. 7 p.
[14]. Semenov A. A., Baraban S. V., Semenova O. O., Voznyak O. M., Vydmysh A. A., Yaroshenko L. V Statistical Express Control of the Peak Values of the Differential-Thermal Analysis of Solid Materials. *Solid State Phenomena.* 291 (2019), 28-41. https://doi.org/10.4028/ www.scientific.net/SSP.291.28
[15]. Paziuk V., Petrova Z., Tokarchuk O., Polievoda Y. Special aspects of soybean drying with high seedling vigor. *Scientific bulletin, Series D: Mechanical Engineering*. 83 (2021). nr. 2, 327-336.
[16]. Gunko I., Babyn I, Aliiev E., Yaropud V., Hrytsun A. Research into operating modes of the air injector of the milking parlor flushing system. *UPB Scientific bulletin, Series D: Mechanical Engineering*, 83 (2021), nr. 2, 297-310.
[17]. Kaletnik H., Mazur V., Gunko I., Ryaboshapka V., Bulgakov V., Raide V., Ilves R., Olt J. Study on performance of compression engine operated by biodiesel fuel. *Agronomy Research*, 18 (2020), 862–887. https://doi.org/10.15159/AR.20.027
[18]. Krivoruchko J.S., Lerman L.B., Skoda N.G. Multicomponent heterogeneous systems; effective dielectric constant and absorption. *Bulletin of NTU “KhPI”.* 66 (2012), 167-173.
[19]. Wallin S. (2000) Engineering turbulence modeling for CFD with a focus on explicit algebraic Reynoldce stress models. Doctoral thesis. Norsteds truckeri, Stockholm, Sweden. 124 p.
[20]. Yaropud V., Honcharuk I., Datsiuk D., Aliiev E. The model for random packaging of small-seeded crops’ seeds in the reservoir of selection seeder’s sowing unit. *Agraarteadus*. 33 (2022), nr. (1), 199-208. https://doi.org/10.15159/jas.22.08
[21]. Kumar S., Raina K. K., Islam, T. Anodic aluminium oxide based humidity sensor for online moisture monitoring of power transformer. *Sensors and Actuators B: Chemical,* 329 (2021), 128908.
[22]. Tsurkan O.V., Gerasimov O.O., Polyevoda Y.A., Tverdokhlib I.V., Rimar T.I., Stanislavchuk O.V. Kinetic features of vibrating and filtration dewatering of fresh-peeled pumpkin seeds. *INMATEH – Agricultural Engineering*, 52 (2017). nr. 2, 69-76.
[23]. Yaropud, V. Analytical study of the automatic ventilation system for the intake of polluted air from the pigsty. *Scientific horizons*. 24 (2021), nr. 3, 19-27. https://doi.org/10.48077/scihor.24(3).2021.19-27
[24]. Nazarova O. Computer Modeling of Multi-Mass Electromechanical Systems. *The Third International Workshop on Computer Modeling and Intelligent Systems (CMIS-2020),* 2608 (2020), 489-498.
[25]. Polievoda, Y., Kupchuk, I., Hontaruk, Y., Furman, I., Mytko, M. Method for determining homogeneity of fine dispersed mixtures based on the software analysis of photo cross-cut of the sample. *Przeglad elektrotechniczny*. 98 (2022). nr. 11, 109-1130. https://doi.org/10.15199/48.2022.11.20
[26]. Vasilevskyi O. M., Sevastianov V.M., Ovchynnykov K. V., Didych V. M., Burlaka S. A. Accuracy of Potentiometric Methods for Measuring Ion Activity in Solutions. *Proceedings of Seventh International Congress on Information and Communication Technology.* 1 (2023), 181-190. https://doi.org/10.1007/978-981-19-1607-6_16