

PL ISSN 0033-2097, e-ISSN 2449-9544

5'2024



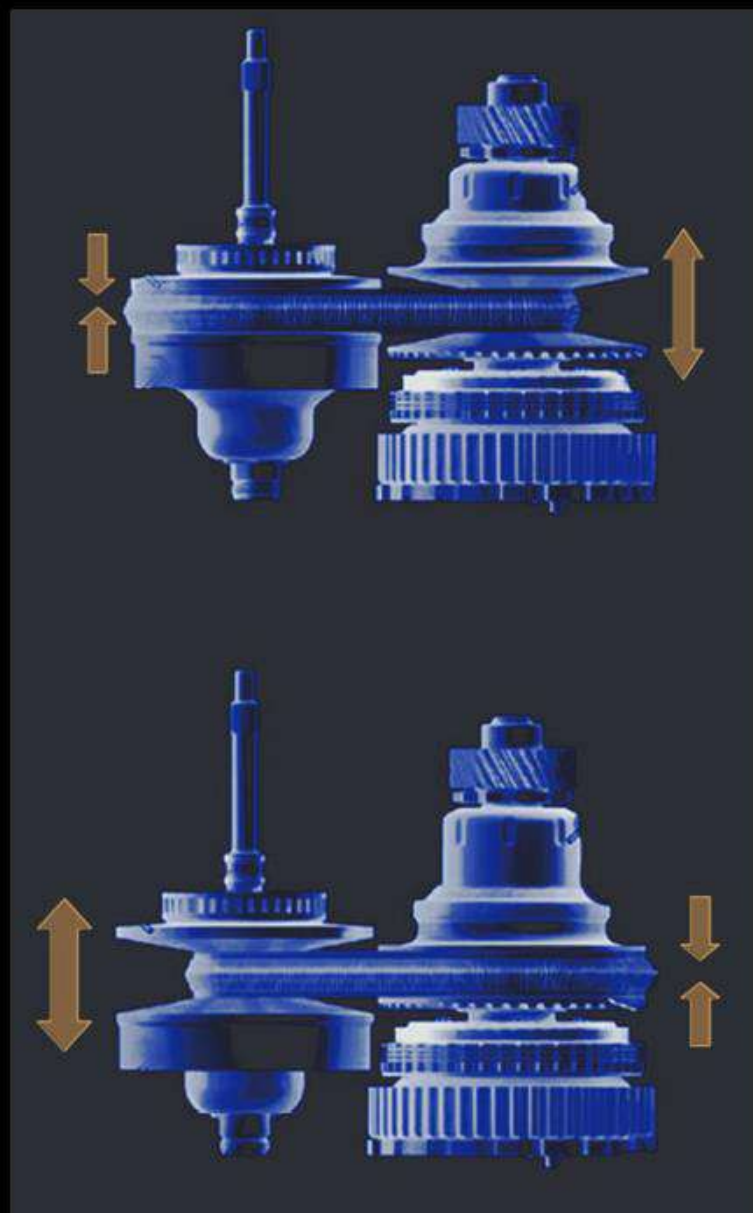
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Analysis and calculation of the dynamic voltage reserve of the converter when working under load in systems of subject regulation by electric drives of direct current

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 wskazać sposoby 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].

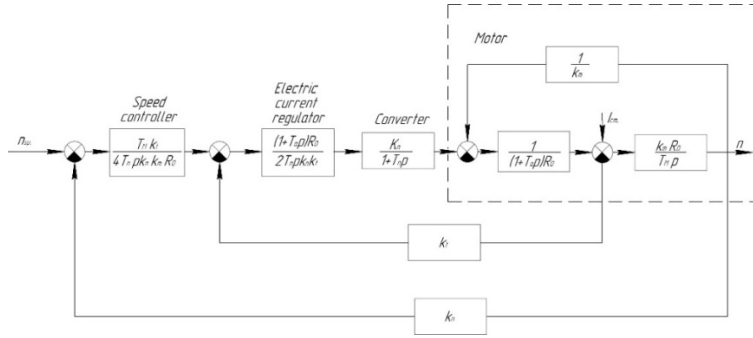


Fig.1. Static system of subordinate regulation by a direct current electric motor: T_M , T_a , T_n – time constants, respectively, electromechanical, electromagnetic armature circuit and small uncompensated current circuit; R_o – armature resistance; coefficients k_m , k_c , k_n – respectively, feedback on the speed, on the armature current, the gain of the converter; $k=1/(C_e \Phi)$; C_e – 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 I_c has the following form [3, 20]:

$$(1) \quad \frac{i R_o}{I_c R_o}(q) = \frac{1}{\frac{1}{8} \cdot q^3 + \frac{1}{2} \cdot q^2 + q + 1} = \frac{1}{N_3(q)}$$

where $q = 4T_n p$ – normalized parameter.

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

$$(2) \quad \frac{i R_o}{I_c R_o}(\tau) = 1 - e^{-2\tau} - \frac{2}{\sqrt{3}} e^{-\tau} \sin \sqrt{3} \tau$$

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

Increasing the voltage of the converter ΔU_{np} can be determined by such a dependence:

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

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

Transfer function conversion (3):

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

where $\frac{1}{N_3(q)} = \frac{i R_o}{I_c R_o}(q)$; $\frac{1}{N_2(q)} = \frac{1}{\frac{1}{8} q^2 + \frac{1}{2} q + 1}$.

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:

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

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 $\frac{\Delta U_{np}}{I_c R_o}(\tau)$ 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 T_{ya} 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.

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

Determination of the maximum value of the function

(5) $\frac{\Delta U_{np,max}}{I_c R_o}$ carried out on a computer at the moment of time $\tau = \tau_{max}$, obtained with (6) and substitution τ_{max} 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 $\frac{\Delta U_{np,max}}{I_c R_o} = f(A, B)$ 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:

$$(7) \quad \frac{\Delta U_{np,max}}{I_c R_o} = 0,5 - 0,89A + 0,81B.$$

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 $\frac{\Delta U_{np,max}}{I_c R_o} = f(A, B)$ you can at $T_a \leq 0,04$ s. Area of minimum values $\frac{\Delta U_{np,max}}{I_c R_o} = f(A, B)$ bounded by the dashed curve.

The zone of values of coefficient A limits the area of positive values of the function $\frac{\Delta U_{np,max}}{I_c R_o} = f(A, B)$ 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.

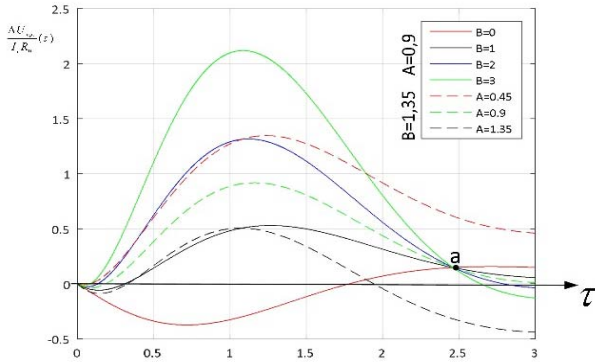


Fig. 2. Curves of instantaneous values of the function $\frac{\Delta U_{np}}{I_c R_o}(\tau)$ at different values of coefficients A and B in a static engine speed control system and a single disturbing influence, $m=2$.

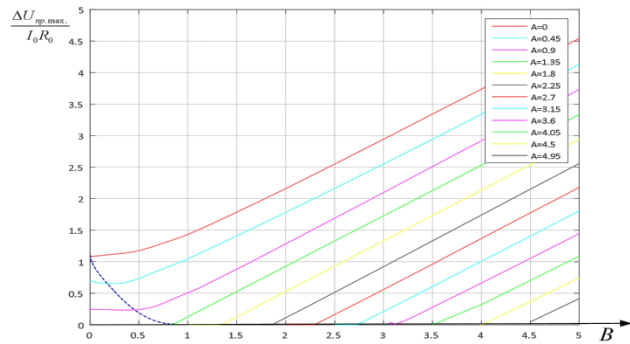


Fig. 3. Curves of maximum function values $\frac{\Delta U_{np,max}}{I_c R_o} = f(A, B)$ at different values of coefficients A and in a static engine speed control system and a single disturbance, $m=2$.

Suppose that the load grows linearly up to the time limit τ_u , 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 $\tau \leq \tau_u$ will look like this:

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

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 $\tau \leq \tau_u$:

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

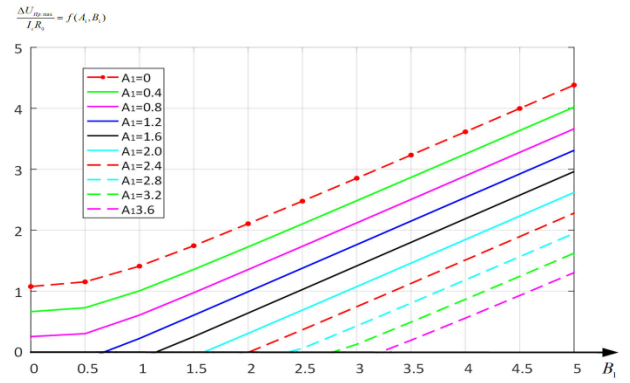


Fig. 4. Curves of maximum function values $\frac{\Delta U_{np,max}}{I_c R_o}$ at different values of coefficients A and B in the static engine speed control system and linearly increasing perturbed at $\tau_u=0.625$ and $m=2$.

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

$$(10) \quad \frac{\Delta U_{np2}}{I_c R_o}(\tau) = 1 - A + F(\tau) - F(\tau - \tau_u)$$

where

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

$F(\tau - \tau_u)$ - similar function $F(\tau)$, but shifted in time to τ_u .

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

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

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

$$(12) \quad \frac{\Delta U'_{np2}}{I_c R_o}(\tau) = F'(\tau) - F'(\tau - \tau_u) = 0$$

where

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

$F'(\tau > \tau_u)$ - similar function $F'(\tau)$, 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 $\frac{\Delta U_{np,max}}{I_c R_o} = f(A, B)$ at $\tau_u = \text{const}$ and at $B > 0,5$ straight line. On the basis of these calculations, the approximation equations of the function were obtained $\frac{\Delta U_{np,max}}{I_c R_o} = f(A, B)$ for $0.5 < B < 10$.

These equations are presented in Table 1.

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

No	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 τ_u , it is possible to determine at which values of A and B the dynamic reserve of the converter is required. For example, when $\tau_u = 5/4$; $B=5$

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

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.

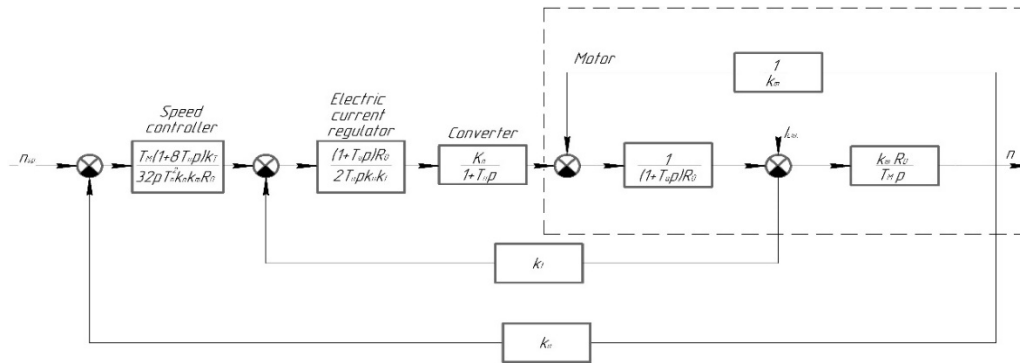


Fig. 5. Astatic system of subordinate regulation of a direct current electric motor

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 influence 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 I_c has the following form [2]:

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

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]:

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

where $\tau = \frac{t}{8T_n}$ relative time, t - is absolute time.

Voltage gain of the converter ΔU_{np} can be determined by such a dependence:

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

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

After converting which we will get the function:

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

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

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 $\frac{q N_2(q)}{N_4(q)}$ corresponds to the transition function

$\frac{1}{2} [-2\tau \cos 2\tau + (\frac{3}{2} + \tau) \sin 2\tau] e^{-2\tau}$, then the transient function of the voltage increase of the converter can be written in the following form:

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

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

Figure 6 shows the curves of instantaneous values of the function $\frac{\Delta U_{np}}{I_c R_o}(\tau)$ for a separate case (solid lines) $A_1=2.0$; $B_1=0..0.75$, constructed according to equation (17). Let's analyze these curves. The presence of a negative part of the increase of the converter ($B_1=0..0.5$) 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 ($B_1 > 0.75$; $A_1=2.0$).

Point a1 of intersection of the curves of instantaneous values $\frac{\Delta U_{np}}{I_c R_o}(\tau)$ 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 $\frac{\Delta U_{np}}{I_c R_o}(\tau)$ (dashed lines) for the case $B_1=0.3125$ and $A_1=2.4..7.2$, built according to the equation (17).

Point a2 of intersection of the curves of instantaneous values $\frac{\Delta U_{np}}{I_c R_o}(\tau)$ 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:

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

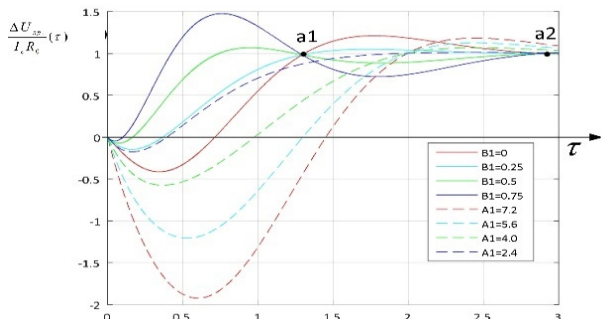


Fig. 6. Curves of instantaneous values of the function $\frac{\Delta U'_{np}}{I_c R_o}(\tau)$ in an astatic system of subordinate engine speed regulation at different values of coefficients A1 and B1 and a unit disturbance.

The determination of the maximum value of function (17) was carried out according to the method described in [18] with the value $\tau = \tau_{max}$ obtained from (18) and substituting τ_{max} 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 $\frac{\Delta U_{np,max}}{I_c R_o}$ first falls, and then the region of relatively large values of B1 increases, where with the decrease of A1 the value $\frac{\Delta U_{np,max}}{I_c R_o}$ 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 $\frac{U_{np,max}}{I_c R_o} = f(A, B)$ on a linear section (table 2).

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

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

Based on the data of fig. 7 starting with curves A₁ = 2,4 ÷ 3,6 on some segments of the value of the function $\frac{U_{np,max}}{I_c R_o} = f(A, B) \approx 1$ will illustrate a straight parallel parameter B_τ.

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 τ_u, 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 < τ_u:

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

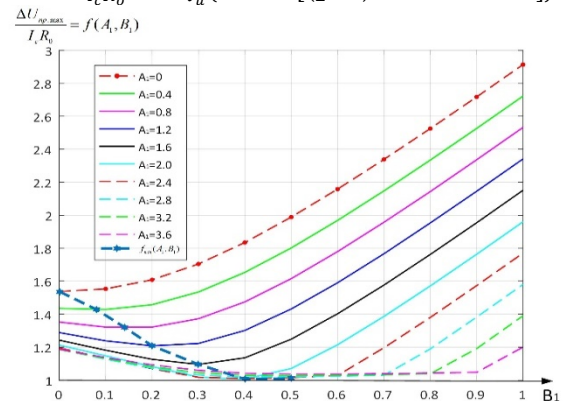


Fig. 7. Curves of maximum function values $\frac{\Delta U_{np,max}}{I_c R_o}$ in an astatic engine speed control system at different values of coefficients A1 and B1 and single disturbance, m=2.

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

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

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

$$(21) \quad \frac{\Delta U_{np2}}{I_c R_o}(\tau) = 1 + F(\tau) - F(\tau - \tau_u)$$

where

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

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

To determine the dynamic voltage margin $\frac{\Delta U_{np,max}}{I_c R_o}$ we differentiate the converter (20) and (21) and the result is set to zero. On the time section τ ≤ τ_u.

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

For a period of time τ ≥ τ_u

$$(23) \quad \frac{\Delta U'_{np2}}{I_c R_o}(\tau) = F'(\tau) - F'(\tau - \tau_u) = 0$$

where

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

where F'(τ-τ_u) - 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 = τ_{max} obtained from (22) and (23) and substituting τ_{max} into equations (19) and (20). The calculation was carried out at τ_u = 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 τ_u increases, the $\frac{\Delta U_{np,max}}{I_c R_o}$ 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 $f(A_1, B_1) = \frac{\Delta U_{np,max}}{I_c R_o}$ at $\tau=0,625$. 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 τ , it is possible to determine the area with certain changes in the B_1 parameter, where the function $\frac{\Delta U_{np,max}}{I_c R_o} \approx 1$, that is, this dependence will be illustrated by a line parallel to the axis of parameter B_1 . For example, $\tau=0,625$; $B_1=0,325$. Then, at all values of A_1 , a voltage margin of more than one is required, except for $A_1=2,4$, where this margin is minimal. It is possible to determine with the values of τ at which values of A_1 and B_1 the necessary reserve voltage of the converter is required.

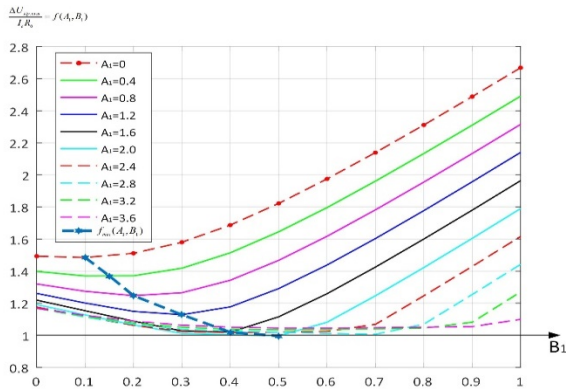


Fig. 8. Curves of maximum function values $\frac{\Delta U_{np,max}}{I_c R_o}$ in the astatic engine speed control system at different values of coefficients A_1 and B_1 , $\tau_u=0,625$ and $m=2$ with a linear limited excitation signal

Table 3. The approximation equation of the function $\frac{\Delta U_{np,max}}{I_c R_o} = f(A, B)$ 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 $\frac{\Delta U_{np,max}}{I_c R_o} = f(A_1, B_1)$
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 τ_u 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.

Authors: DUBIK Viktor – PhD in Engineering, Associate Professor, Podillia State University (32316, 12, Shevchenko Str., Kamianets-Podilskyi, Khmelnytskyi region, Ukraine), e-mail: vmdubick@gmail.com; KAMISHLOV Vitalii – PhD in Engineering, Associate Professor, Podillia State University (32316, 12, Shevchenko Str., Kamianets-Podilskyi, Khmelnytskyi region, Ukraine), e-mail: ketem@pdatu.edu.ua; TKACH Oleg – Dr. Agricultural Sc., Associate Professor, Head of the Department of Energy Saving Technologies and Energy Management, Podillia State University (32316, 12, Shevchenko Str., Kamianets-Podilskyi, Khmelnytskyi region, Ukraine), e-mail: oleg.v.tkach@gmail.com; HORBOVY Oleg – assistant, Podillia State University (32316, 12, Shevchenko Str., Kamianets-Podilskyi, Khmelnytskyi region, Ukraine), e-mail: Oleg.Gorbovuy@gmail.com; MAZUR Viktor – PhD in Agricultural Sciences, Professor, Rector, Vinnytsia National Agrarian University (21008, 3 Sonyachna str., Vinnytsia, Ukraine), e-mail: mazur@vsau.vin.ua; KUPCHUK Ihor – PhD in Engineering, Associate Professor, Deputy Dean for Scientific Research of Faculty of Engineering and Technology, Vinnytsia National Agrarian University (21008, 3 Sonyachna str., Vinnytsia, Ukraine), e-mail: kupchuk.igor@i.ua; PANTSYREVA Hanna – PhD in Agricultural Sciences, Associate Professor, Vinnytsia National Agrarian University (21008, 3 Sonyachna str., Vinnytsia, Ukraine), e-mail: apantsyreva@ukr.net; ALIEKSIIEVA Olha – PhD in Economics, Senior lecturer, Vinnytsia National Agrarian University (21008, 3 Sonyachna str., Vinnytsia, Ukraine), e-mail: olga_aleksieieva@ukr.net.

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