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THE INFLUENCE OF BRUSHLESS MAGNETOELECTRIC TACHOGENERATOR SIGNAL PULSATIONS ON THE SERVO SYSTEM TUNING

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The paper is devoted to the study of operating modes and features of tuning of a servo system containing a brushless magnetoelectric tachogenerator in the angular speed control loop of an executive motor. Features of tuning of the internal loop of angular speed for compensation of electromechanical time constant taking into account pulsations of the tachogenerator signal are studied. Dependences of the signal ripple coefficient at the tachogenerator filter output, the values of the signal ripple swing in the angular speed loop and the effective current value on the parameters of the system operation mode are given. The influence of the system tuning parameters on the performance indexes of angular speed control is studied. The approach to tuning of the servo system taking into account the parameters of the angular speed loop while providing a given stability margin in phase is considered. The results of studies of the servo system are given. References 16, figures 15, table 1.
***Key words*:** servo system, brushless magnetoelectric tachogenerator, tuning of automatic control system, phase stability margin, signal ripples.

A feature of the development of some electromechanical servo systems is that the actuating motor often drives a mechanism with a relatively large moment of inertia. As a result, to compensate for the relatively large electromechanical time constant of the motor with the control object, it is necessary to tune the inner loop of the servo system with a motor angular speed sensor [1–4]. Such sensors are subject to certain requirements.

Nowadays, in many cases, DC collector tachogenerators are used as angular speed sensors [5–10]. The disadvantages of such tachogenerators are caused by the presence of mechanical commutators, which limits the resource of their operation, causes voltage drop and pulsations on the rotating mechanical contact. To partially eliminate these disadvantages, the plates of mechanical contacts are made of an alloy containing 95% silver. The use of DC tachogenerators makes it possible to obtain an isolated analog voltage signal proportional to the angular speed of the rotating motor.

At the same time, to eliminate mechanical contacts on the rotating rotor, brushless designs of tachogenerators with permanent magnets on the rotor are developed and used, in which a constant analog signal is obtained by means of an electronic circuit of rectification of phase alternating EMFs of the stator winding [11–13]. The problem in the development of such brushless tachogenerators is the presence of pulsations of the output rectified signal due to the peculiar form of the phase alternating stator EMFs. One of the directions of overcoming this problem is the choice of such a form of EMF at which the output ripples are minimized.

The influence of the pulsations of the angular speed sensor signal should be taken into account when tuning the angular speed control closed loop to compensate for the electromechanical time constant of the motor and mechanism, as well as when tuning the entire servo system. Preliminary studies have shown that

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the presence of pulsations in the tachogenerator signal due to relatively large values of the angular speed controller gain leads to the appearance of pulsations of the current and torque of the motor. To reduce these pulsations, an additional first-order low frequency filter must be introduced in the speed control loop. And this, in turn, leads to deterioration of the dynamic characteristics of the servo system. Thus, the factors affecting the tuning of the servo system are the values of the pulsations of the tachogenerator signal and other variables, the value of the smoothing filter time constant, as well as the criteria for tuning the angular speed control loop and the external control loop of the rotation angle.

The purpose of the paper is to determine the relationships between the values of the time constant of the tachogenerator signal filter and the parameters of the angular speed and motor shaft rotation angle controllers to assess the influence of these parameters on the tuning the servo system and the quality of regulation, taking into account the presence of pulsations in the signal of the brushless magnetoelectric tachogenerator (BMT).

The main material and research results. The BMT is generally an m-phase AC electric machine [14, 15]. Fig. 1 shows a three-phase system of stator winding EMFs, which in the simplest case are described by sinusoidal functions

$$e_A = k_{m\,G}\omega\sin\theta;\quad e_B = k_{m\,G}\omega\sin(\theta - 2\pi/3);\quad e_C = k_{m\,G}\omega\sin(\theta - 4\pi/3),\tag{1–3}$$

where k_{mG}, ω are constant coefficient and angular speed of rotation of the generator rotor; θ is electric angle of rotation of the rotor shaft, which is defined as $\theta = p\omega t$, where p is number of pole pairs of the rotor; t is time.

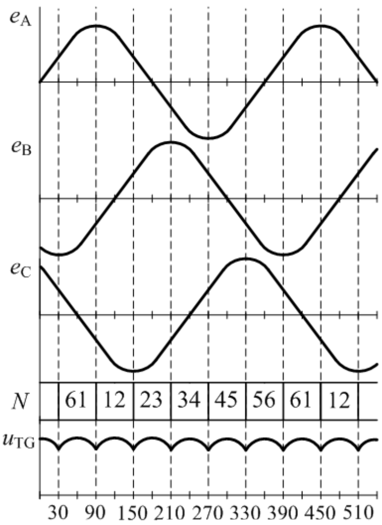

Fig. 1

To form an analog voltage signal proportional to the angular speed of the rotating motor, a three-phase bridge active rectifier based on controlled keys with double-sided conductivity, such as MOSFETs, is used (Fig. 2). The conduction intervals of the controlled keys are marked with the letter N in Fig. 1. In this case, the output signal of the tachogenerator rectifier at each repeatability interval of 60 electrical degrees is described as a sum of two phase EMFs, e.g. at the interval N=61 two variables are summed – e_A and e_B. Six transistors $S1...S6$ (Fig. 2) are numbered according to the sequence of their turning on. The two-digit number N indicates the numbers of the pairs of transistors that are in the conduction state.

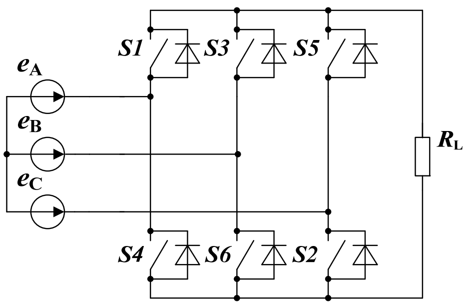

Fig. 2

To evaluate the quality of the tachogenerator signal, the pulsation coefficient can be used, which can be calculated by simple formulas based on the signal parameters u_{TG} or the induction distribution curve b in the tachogenerator air gap

$$k_{P1} = 100\frac{u_{\max} - u_{\min}}{u_{\max} + u_{\min}} = 100\frac{2b_{60} - (b_{90} + b_{30})}{2b_{60} + (b_{90} + b_{30})},\tag{4}$$

where u_{max}, u_{min}, are maximum and minimum values of the signal u_{TG}; b_{30}, b_{60}, b_{90} are relative values of the induction b distribution curve (Fig. 3) in the air gap of the tachogenerator at 30, 60 and 90 electrical degrees at the first quarter of the half-wave of the EMF curve. The table the parameters of two variants of induction distribution curves in the air gap. The first variant corresponds to the sinusoidal form, and the second variant corresponds to the form at the value of the ripple coefficient equal to one.

variant	b_{30}	b_{60}	b_{90}	k_{P1}, %
1	0,5	0,866	1	7, 176
2	0,95	0,9947	1	1

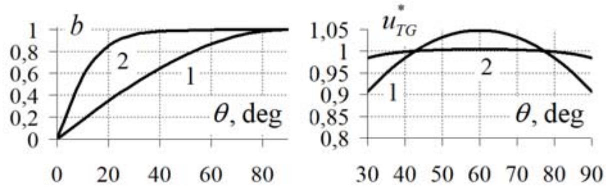

Fig. 3

In this paper, a tachogenerator with the output signal according to the second variant is used in the research of the servo system. To model the tachogenerator, the relative signal u^*_{TG}, normalized in such a way that its average value is equal to one, is used. The signal variation curves u^*_{TG} at sixty-degree repeatability interval are shown in Fig. 3. Relative normalized signal u^*_{TG} is determined by the formula

$$u^*_{TG} = u_{TG} / u_{av} \,, \tag{5}$$

where u_{av} is average value of the tachogenerator output signal u_{TG} (Fig. 1).

The structures of servo systems are known and, as a rule, they contain an inner loop closed by angular speed and an outer loop to regulate the rotor rotation angle. To study the operation modes of the servo system, we will use the mathematical model of the motor, which corresponds to the model of a DC collector motor or, with some assumptions, to the model of the electric drive structure "brushless permanent magnet motor - voltage inverter"

$$L\frac{di}{dt} = -Ri - e + u_\omega; \qquad e = u^*_e k_m \,\omega; \qquad J\frac{d\omega}{dt} = M - M_L; \qquad \frac{d\alpha}{dt} = \omega; \tag{6–9}$$

$$\Delta M = M - M_L; \qquad M_L = M_{L1} sign(\omega); \qquad M = k_m i \,, \tag{10–12}$$

where i, e, u_ω are motor current and EMF, as well as the voltage in the DC link of the voltage inverter or the rotor of the collector motor; u^*_e is modulating function of EMF with a unit mean value, which takes into account the ripple EMF; R, L are active resistance and inductance of the motor; k_m is motor torque coefficient; J is moment of inertia on the shaft of the motor rotor; ΔM, M, M_L are dynamic torque, motor torque and mechanical load torque; M_{L1} is mechanical resistance torque; α is a rotor rotation angle.

On the basis of equations (6-12) we write down the motor transfer functions

$$\frac{i(p)}{u_\omega(p) - e(p)} = \frac{1/R}{T_E\, p + 1}; \qquad \frac{\omega(p)}{\Delta M(p)} = \frac{1}{J\,p}; \qquad \frac{\omega(p)}{u_\omega(p)} = \frac{1/k_m}{T_M\, p + 1}, \tag{13–15}$$

where T_M, T_E are electromechanical and electromagnetic time constants.

Finally, Fig. 4 shows the structural diagram of the servo control system consisting of the executive mo-tor, the BMT and its output signal filter, the angular speed and angular position controllers of the motor rotor. It can be noted that the structure of the system does not have an internal current control loop. It will be shown be-low that the value of the electromagnetic time constant of the brushless motor with permanent magnets, which is used in the system, is significantly less than the value of the time constant of the tachogenerator filter. Therefore, the electromagnetic time constant of the motor will not affect the main operating mode of the servo system. In this case, there is no need to correct and consider the current loop.

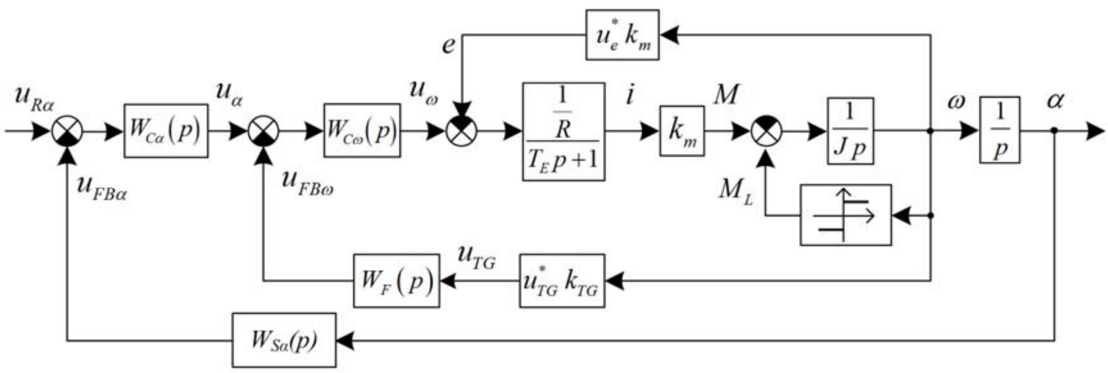

Fig. 4

Let us supplement the description of the closed loop automatic motor angular speed control with formulas for determining the mismatch $u_{U\omega}(p)$ and tachogenerator signal $u_{TG}(p)$, as well as transfer functions of the angular speed controller $W_\omega(p)$ and tachogenerator filter $W_F(p)$,

$$u_{U\omega}(p) = u_\alpha(p) - u_{FB\omega}(p); \qquad u_{TG}(p) = u^*_{TG} k_{TG}\, \omega \,, \tag{16, 17}$$

$$W_{C\omega}(p) = \frac{u_\omega(p)}{u_{U\omega}(p)} = \frac{k_{C\omega}(T_{C\omega}\, p + 1)}{p}; \qquad W_F(p) = \frac{u_{BF\omega}(p)}{u_{TG}(p)} = \frac{k_F}{T_F\, p + 1}; \tag{18, 19}$$

where $u_\alpha(p)$ is the rotor angular speed reference signal, which is the output signal of the PI-angle controller; $u_{FB\omega}(p)$ is the feedback signal at the filter output; $k_{C\omega}$, $T_{C\omega}$ are the gain and time constant of the PI-controller; k_F, T_F are the gain and time constant of the filter at the tachogenerator output; k_{TG} is the gain of the tachogenerator. Note that the signal at the output of the tachogenerator is determined taking into account the previously obtained relatively normalized modulating signal u_{TG}^* accordingly to the form of the real tachogenerator signal. Thus, the pulsations of the tachogenerator output signal are taken into account.

The outer loop of the servo system is formed by feedback from the shaft rotation angle sensor $W_{S\alpha}(p)$ of the actuating element of the mechanism and the rotation angle controller $W_{C\alpha}(p)$. In this paper, we will limit ourselves to the consideration of a system with second-order astatism with a PI rotational angle controller. The external loop is described by the equations

$$u_{U\alpha}(p)=u_{R\alpha}(p)-u_{FB\alpha}(p); \tag{20}$$

$$W_{C\alpha}(p)=\frac{u_\alpha(p)}{u_{U\alpha}(p)}=\frac{k_{C\alpha}(T_{C\alpha}p+1)}{p}; \qquad W_{S\alpha}(p)=\frac{u_{BF\alpha}(p)}{\alpha(p)}=\frac{k_{S\alpha}}{T_{S\alpha}p+1}, \tag{21, 22}$$

where $u_{R\alpha}(p)$ is the rotation angle reference signal; $k_{C\omega}$, $T_{C\omega}$ are the gain and time constant of the rotation angle PI-controller; $k_{S\alpha}$, $T_{S\alpha}$ are the gain and time constant of the rotation angle sensor.

To compensate for the relatively large value of the electromechanical time constant, it is assumed to be equal to the time constant of the angular speed PI controller $T_{C\omega}=T_M$, then we write the transfer function of the closed loop angular speed control in the form of

$$\frac{\omega(p)}{u_\alpha(p)}=\frac{k_\omega}{T_1^2p^2+2\xi T_1p+1}, \tag{23}$$

where k_ω, T_1, ξ are the gain, time constant and damping coefficient of the second-order link. In this case, the parameters of the transfer function (23) are determined by the following equations

$$k_\omega=\frac{1}{k_{TG}k_F}; \qquad T_1=\sqrt{\frac{k_mT_F}{k_{C\omega}k_{TG}k_F}}. \tag{24, 25}$$

For a stable oscillating link, the condition $0\le\xi\le1$ is true. Thus, the tuning of the second-order control system (23) and the value of the transfer coefficient of the angular speed PI controller under the condition $T_{C\omega}=T_M$ is determined only by the values of the damping coefficient ξ [16] and the filter time constant T_F at the tachogenerator output

$$k_{C\omega}=\frac{k_m}{4\xi^2T_Fk_{TG}k_F}. \tag{26}$$

Then the gain of an open loop of angular speed control is defined as the product of all gain of the loop

$$k_{OLS\omega}=k_{C\omega}k_{TG}k_F/k_m. \tag{27}$$

Due to the relatively large value of the moment of inertia on the actuator shaft, the pulsations of the tachogenerator signal will practically have no effect on the character of change of the angular speed and rotor angle. Therefore, in this study we are interested in the parameters of the tachogenerator output signal, the signal at the output of the tachogenerator filter, the signal at the output of the angular speed controller and motor current. That is, at this stage we will study the tunings of the closed loop angular speed, which is internal to the servo system. At the same time, we can vary the values of filter time constant T_F and damping coefficient ξ, as a result of which we can determine the value of angular speed controller gain $k_{C\omega}$, and the time constant of PI controller is already determined and set in the condition $T_{C\omega}=T_M$.

Parameters of signals at the output of the tachogenerator are presented in Table, and for further studies we choose the best of them, i.e. the second variant. To evaluate the quality of signals in the system we use such parameters:

– signal pulsation coefficient at the output of the tachogenerator filter

$$k_{PF} = \frac{100\Delta u_F}{2u_{Fav}}, \tag{28}$$

where Δu_F, u_{Fav} are pulsation swing of the signal at the tachogenerator filter output and the average value of this signal;

– relative values of signal pulsation swing at the tachogenerator filter output and at the angular speed controller output

$$\Delta u_F^* = \frac{100\,\Delta u_F}{U_{F3000}}; \qquad \Delta u_\omega^* = \frac{100\,\Delta u_\omega}{U_{\omega\max}}, \tag{29, 30}$$

where Δu_ω is the pulsation swing of the signal at the output of the angular speed PI controller; U_{F3000}, $U_{\omega\max}$ are values of the tachogenerator signal at the nominal speed, equal to 3000 rpm, and the maximum value of the voltage at the controller output;

– relative value of motor current ripple swing

$$\Delta i^* = 100\,\Delta i / I_N, \tag{31}$$

where Δi is current ripple swing; I_N is nominal current value. To estimate the magnitude of a direct current that has pulsations, the current effective value is used, the magnitude of which in this case will differ from its average value;

– relative value of the motor current effective value

$$I_{ef}^* = 100\,I_{ef} / I_N, \tag{32}$$

where I_{ef} is the current effective value.

First, we study the properties of a single tachogenerator with a first-order filter (19) at the output, which rotates at a given and constant angular speed. Fig. 5 shows the dependences of the pulsation coefficient k_{PF} of the signal at the filter output, as well as the relative magnitude of the pulsation swing Δu_F^* on the rotation speed at three values of the filter time constant T_F – 0.01; 0.02 and 0.04 s. All characteristics in Fig. 5 and in the figures below for these three values T_F of the time constant are designated respectively by numbers from 1 to 3. Fig. 5 shows that the reference value of the pulsation coefficient of 1% is maintained only at the lowest rotational speed, and as it increases, it decreases significantly due to the influence of the low frequency filter. All further studies will be carried out at these three values of time constant T_F.

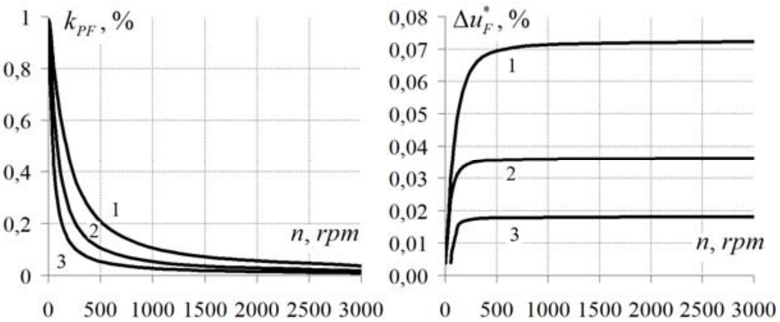

Fig. 5

Next, let's perform an example of calculation of operation modes of the angular speed loop, the input of which is supplied with a constant speed reference signal at $\xi = 0,7$ and three values of the filter time constant. For the example calculation we have chosen a motor with the following parameters: rated power – 180 W; maximum rotation speed – 3000 rpm. In addition, the motor model (6-12) and the system is characterized by the parameters: $k_m = 0,08594$ Vs, $L = 4,54 \cdot 10^{-5}$ Hn, $R = 0,1$ Ohm, $I_N = 12$ A, $U_{F3000} = 15$ V, $U_{\omega\max} = 27$ V, $T_E = 4,54 \cdot 10^{-4}$ s.

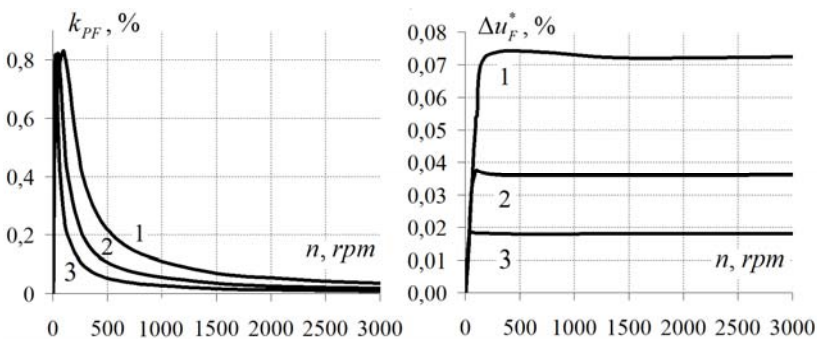

Fig. 6

Fig. 6 shows the dependences of the pulsation coefficient k_{PF} of the signal at the filter output and the relative values of the ripple swing Δu_F^* on the rotation speed *n*, but for a tachogenerator that operates in the complex of the servo system (Fig. 4). In this study, the EMF curve is assumed to be perfectly smooth, i.e.,

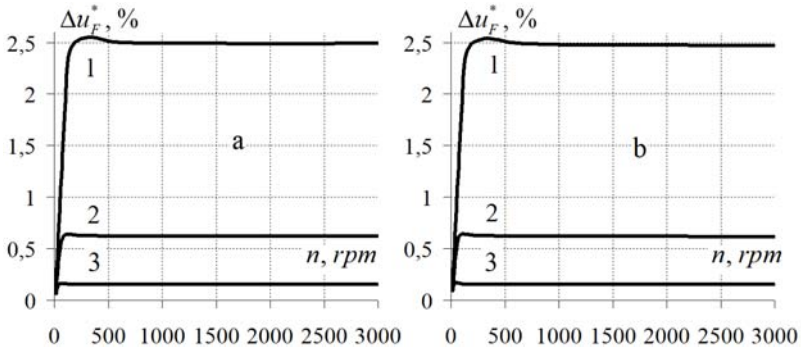

Fig. 7

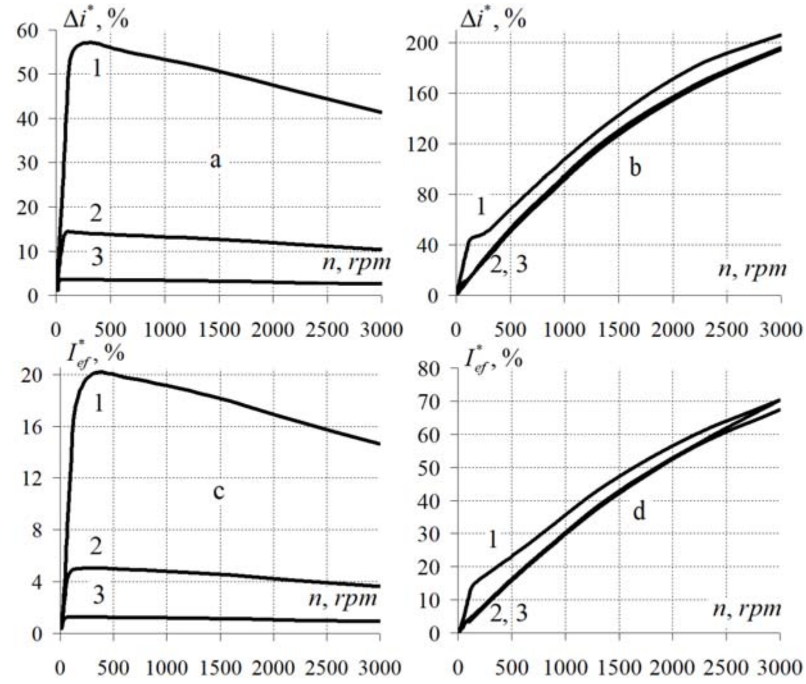

Fig. 8

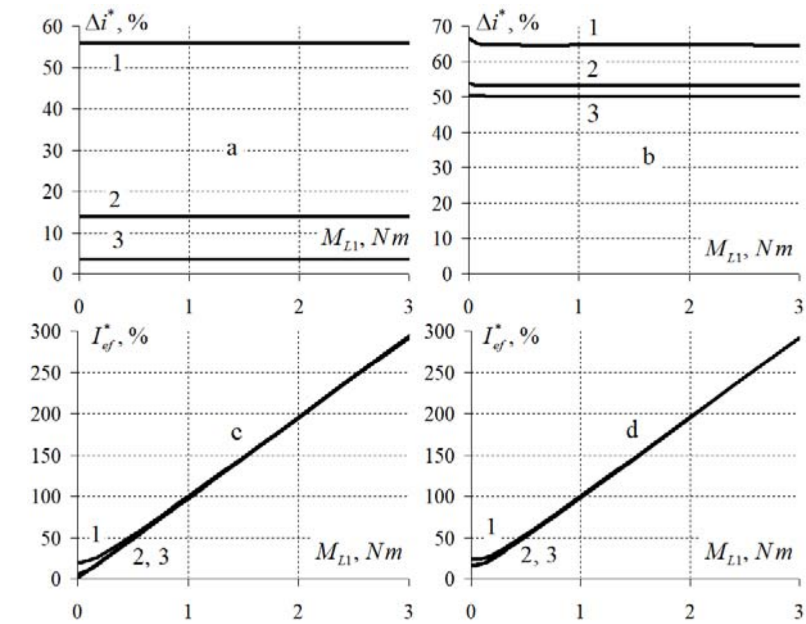

Fig. 9

the instantaneous values of the modulating EMF function u_e^* are equal to unity. Most noticeable in these figures is the difference of the graphs in the region of small values of rotation speed. This difference arises due to the influence of tachogenerator pulsations on the rotational speed pulsations, since at low frequencies the filtering capabilities of the system are weakened.

Fig. 7, *a*, *b* shows the dependences of the relative values of the signal ripple swing Δu_ω^* at the output of the angular speed PI controller on the rotation speed *n* for two variants of calculation of the processes in the inner loop of the servo system. These variants differ in the representation of the EMF perfectly smoothed (Fig. 7*, a*) and taking into account the EMF signal ripples (Fig. 7, *b*), which are possible in the case of controlling a brushless permanent magnet motor supplied from a voltage inverter with the transistors' states switched on at intervals with an angular extent of 120 electric degrees. The modulating EMF function u_e^* in the case of sinusoidal form of alternating EMFs of the stator windings of the brushless motor has the form presented in Fig. 3 (variant 1). Comparison of Fig. 7, *a, b* shows that possible EMF pulsations in the system loop practically do not affect the magnitude of signal pulsations at the output of the motor angular speed controller.

Fig. 8 shows the dependences of the relative magnitude of the current ripple swing Δi^* and the relative effective current value I_{ef}^* on the rotation speed *n* at smooth (*a, c*) and pulsating (*b, d*) forms of EMF.

Fig. 9 show the dependences of the relative magnitude of the current ripple swing Δi^* and the relative effective current value I_{ef}^* on the magnitude of the mechanical load torque M_{L1} under the smooth (a, c) and pulsating (b, d) forms of EMF, and under the condition $n = 500$ rpm .

Fig. 10 shows the dependences of the previously mentioned relative values of the signal ripple swing Δu_{ω}^{*} at the output of the tachogenerator filter, the signal ripple swing Δu_{ω}^{*} at the output of the angular speed controller, the relative magnitude of the current ripple Δi^{*}, relative effective current value I_{ef}^{*}, as well as response time t_R and overshooting σ from the damping coefficient value ξ at perfectly smoothed EMF, rotation speed $n = 500$ rpm and three given values of filter time constant T_F – 0,01; 0,02 and 0,04 s.

Fig. 11 shows the dependences of the gain $k_{OLS\omega}$ of the open loop of angular speed control and the time constant T_1 of the second-order link (23) on the value of the damping coefficient ξ at three given values of the filter time constant T_F – 0.01; 0.02 and 0.04 s.

Thus, as a result of studies of the angular speed loop, the time constant T_1 of its transfer function (23) can be determined, and the gain k_{ω} is known because it is determined by the angular speed feedback parameters. Now we can write the transfer function of the open loop servo system in the form of

$$W_{OLS}(p) = \frac{k_{OLS\alpha}\left(T_{C\alpha}p + 1\right)}{\left(T_1^2 p^2 + 2\xi T_1 p + 1\right)\left(T_{S\alpha}p + 1\right)p^2}, \quad (33)$$

where $k_{OLS\alpha} = k_{C\alpha}k_{\omega}k_{S\alpha}$ is the gain of the open loop system.

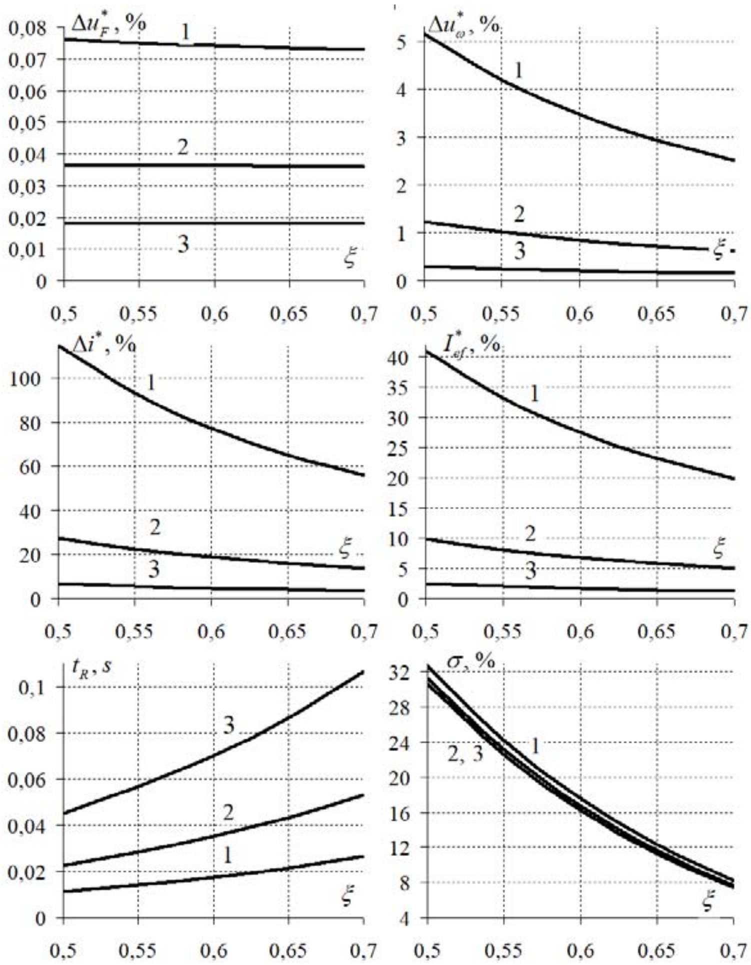

Fig. 10

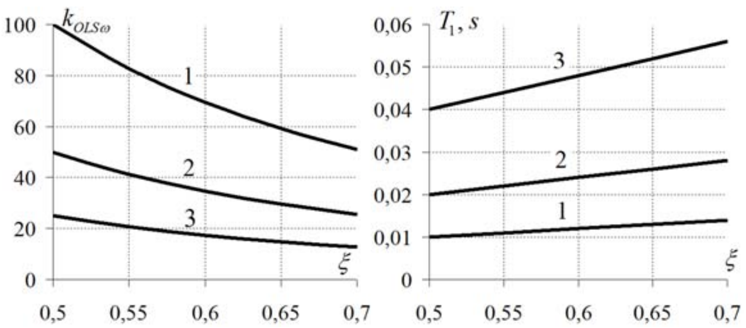

Fig. 11

For the transfer function of the open loop system (31), the amplitude and phase frequency characteristics can be obtained

$$A(\omega) = \frac{k_{OLS\alpha}\sqrt{1 + T_{C\alpha}^2\omega^2}}{\omega^4\sqrt{1 + 2T_1^2\omega^2\left(2\xi^2 - 1\right) - T_1^4\omega^4}\sqrt{1 + T_{S\alpha}^2\omega^2}}; \qquad A_L(\omega) = 20\log A(\omega); \quad (34, 35)$$

$$\varphi(\omega) = -\pi - \operatorname{arctg}T_{S\alpha}\omega + \operatorname{arctg}T_{C\alpha}\omega - \operatorname{arctg}\frac{2\xi T_1\omega}{1 - T_1^2\omega^2}. \quad (36)$$

The condition for tuning a stable control system is to provide a sufficient phase stability margin γ_S at the cutoff frequency ω_C [16]. The stability margin γ_S in phase is determined on the basis of the dependence

$$\gamma(\omega) = \pi + \varphi(\omega) = -\mathrm{arctg} T_{S\alpha}\omega + \mathrm{arctg} T_{C\alpha}\omega - \mathrm{arctg}\frac{2\xi T_1\omega}{1 - T_1^2\omega^2}. \tag{37}$$

Ensuring sufficient phase stability margin γ_S is possible by selecting a certain ratio of time constants $T_{C\alpha}$ and T_1 under the condition $T_{S\alpha} \ll T_1 < T_{C\alpha}$. In this paper, three values of the filter time constant T_F – 0.01; 0.02 and 0.04 s – were taken for the speed loop studies, and for further development of the servo system we take the smallest of these values. Then at three values of damping coefficient ξ – 0,5; 0,6 and 0,7 correspond to the values of oscillating link time constant T_1 – 0,01; 0,012 and 0,014 s, from which we also choose the smallest value – 0,01s. Since the main focus of the paper is on the influence of the tachogenerator signal on the system tuning, we do not take into account the time constant $T_{S\alpha}$ of the rotation angle sensor here. This is true if this value is more than an order of magnitude smaller than the time constant T_1.

It is known that for second-order astatic systems the static error of the input signal processing and the error on the first-order derivative are equal to zero, and errors on derivatives of higher orders are inversely proportional to the gain $k_{OLS\alpha}$ of the open-loop system. Therefore, the criterion for tuning the servo system can be considered as obtaining the largest value of this coefficient under the condition of ensuring an acceptable phase stability margin γ_S. In recommendations on tuning of control systems it is usual to choose the value of phase margin γ_S from the range of values 30...60 degrees.

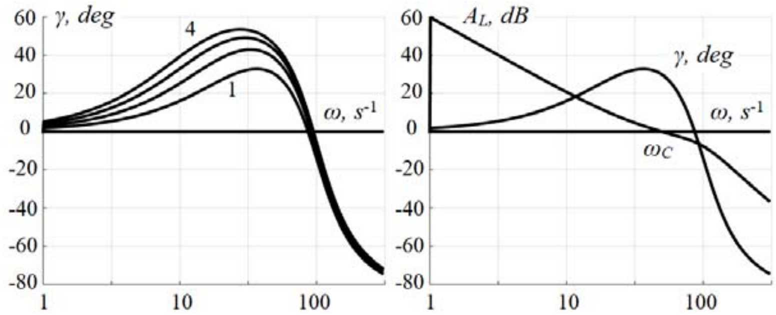

Fig. 12

Fig. 12 shows the family of dependencies $\gamma(\omega)$ (37) for $\xi = 0,5$, $T_F = 0,01$ s, $T_1 = 0,01$ s and four values $T_{C\alpha}$ – 0.04; 0.06; 0.08 and 0.1 s, which are designated by numbers from 1 to 4. For each of these dependencies, for a given desired value of the phase margin $\gamma_S = 30$ grad, it is possible to determine the cutoff frequency ω_C, the value of which determines the position of the amplitude frequency characteristic $A_L(\omega)$. Then it is possible to determine the gain $k_{OLS\alpha}$ of the open-loop servo system at the cutoff frequency using the formula

$$k_{OLS\alpha} = \frac{\omega_C^4\sqrt{1 + 2T_1^2\omega_C^2\left(2\xi^2 - 1\right) - T_1^4\omega_C^4}\sqrt{1 + T_{S\alpha}^2\omega_C^2}}{\sqrt{1 + T_{C\alpha}^2\omega_C^2}}. \tag{38}$$

Fig. 12 shows the amplitude and phase frequency characteristics at $T_{C\alpha} = 0,04$ s, $k_{OLS\alpha} = 994,9$ and $\gamma_S = 30$ deg. Studies have shown that for a family of phase characteristics at a given value of the phase stability margin, it is possible to choose such a ratio of time constants $T_{C\alpha}$ and T_1, at which the maximum value of the gain $k_{OLS\alpha}$ is achieved.

Fig. 13 shows the dependences of the gain $k_{OLS\alpha}$ of the open-loop servo system and cutoff frequency ω_C on the value of the time constant $T_{C\alpha}$ of the PI controller at the time constant $T_1 = 0,01$ s of the angular speed control loop and a given stability margin in phase $\gamma_S = 30$ deg, from which it is possible to determine the maximum value of the gain $k_{OLS\alpha} = 1005,7$ at the cutoff frequency $\omega_C = 52,36$ s^{-1} and time constant $T_{C\alpha} = 0,0425$ s. And such gain maxima $k_{OLS\alpha}$ can be deter-

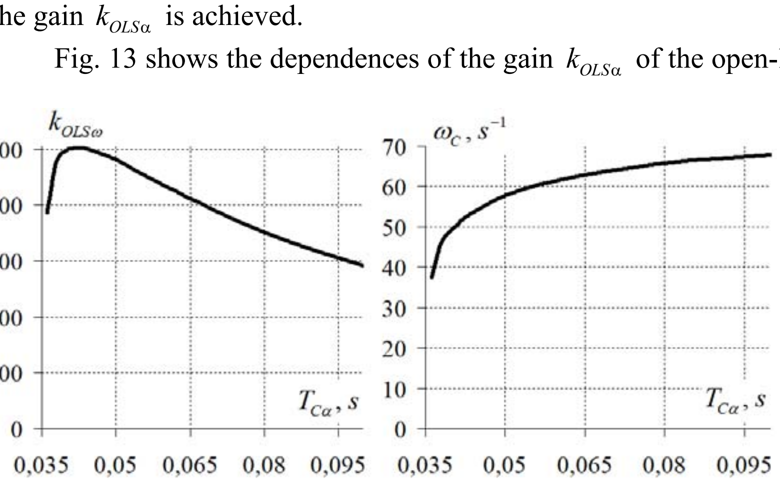

Fig. 13

mined for any value of time constant T_1.

In further studies of the servo system we assume such its parameters: $T_1 = 0{,}01\,\text{s}$, $k_{OLS\alpha} = 1005{,}7$, $T_{C\alpha} = 0{,}0425\,\text{s}$. Let us study the operation mode when the input reference signal of the system is given as

$$u_{R\alpha}(t) = a_1 \sin(2\pi f_1 t), \qquad (39)$$

where a_1, f_1 are amplitude and frequency of signal oscillations.

The error of processing of such a reference signal by the system will also be described by a periodic function

$$\varepsilon_\alpha(t) = u_{R\alpha}(t) - \alpha(t), \qquad (40)$$

is similar in form to (39), but its sinusoidal form may be distorted due to the tachogenerator signal pulsations and also due to the effect of dry friction torque when the motor rotation direction is changed. Therefore, the amplitude of the equivalent sinusoidal variable that describes the error of the reference signal (39) can be determined to estimate this error. Then, based on the effective value of the error variable (40), we can determine its equivalent amplitude

$$\varepsilon_{\alpha 1} = \sqrt{2}\,\varepsilon_{\alpha ef}\,. \qquad (41)$$

To evaluate the characteristics of the operation mode we use such parameters:

– relative amplitude of the equivalent sinusoidal variable of sinusoidal form, which corresponds to the error of the processing of the reference signal $\varepsilon_\alpha(t)$,

$$\varepsilon^*_{\alpha\max} = \frac{100\,\varepsilon_{\alpha 1}}{a_1} \qquad (42)$$

– is the effective current value I_{ef} at the oscillation period of the reference signal.

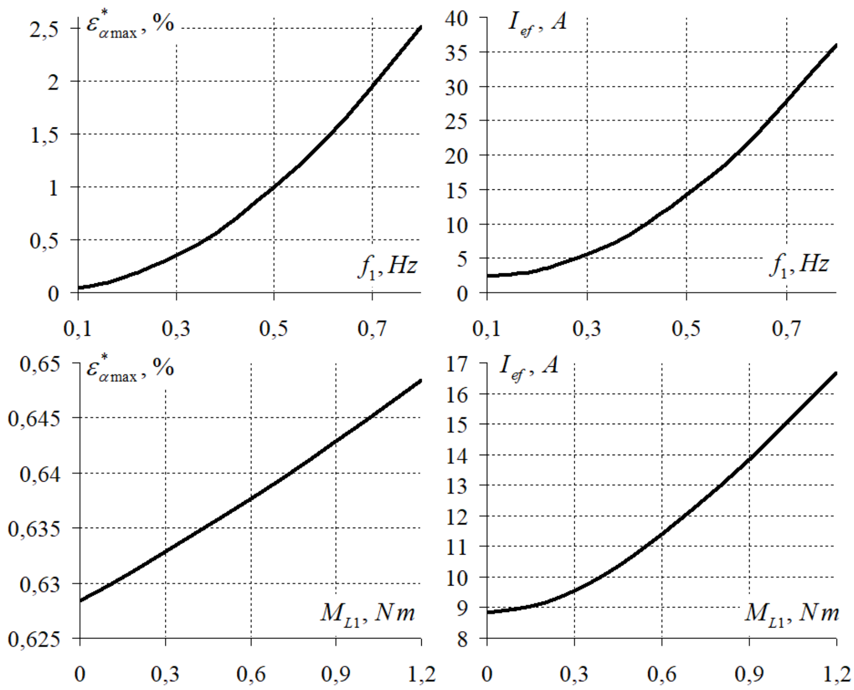

Fig. 14

Fig. 14 shows the dependences of the relative equivalent amplitude $\varepsilon^*_{\alpha\max}$ and the effective current value I_{ef} on the oscillation frequency of the signal f_1 at a_1=3,33 rad and $M_{L1} = 0$. Fig. 14 shows also the dependences of the same parameters on the value of the mechanical resistance torque M_{L1} at $f_1 = 0{,}4\,\text{Hz}$.

Fig. 15 shows the plots of instantaneous values of the variables of the servo system (Fig. 4) when operating the input signal (39) at $M_{L1} = 0{,}2\,\text{Nm}$, where we can see the influence of the tachogenerator signal ripples, which is most evident for the stator current and motor torque variables.

Conclusions. The parameters for tuning the motor angular speed control loop are the tachogenerator filter time constant and the damping coefficient. Using this time constant allows signals pulsations in the loop to be reduced, and selecting the damping coefficient value allows a stable angular speed loop to be set up. In this case, the electromechanical time constant of the motor and mechanism is compensated, the angular speed controller gain is determined, as well as the gain and time constant of the second-order oscillatory link, which describes the angular speed loop and is an internal link in the servo system.

The condition for tuning stable servo system is the criterion of a sufficient phase stability margin at the cut-off frequency. As a result of tuning the servo system by varying the time constant of the angular position controller, the maximum value of the open-loop servo system gain was determined, at which the minimum value of the input signal processing error can be obtained.

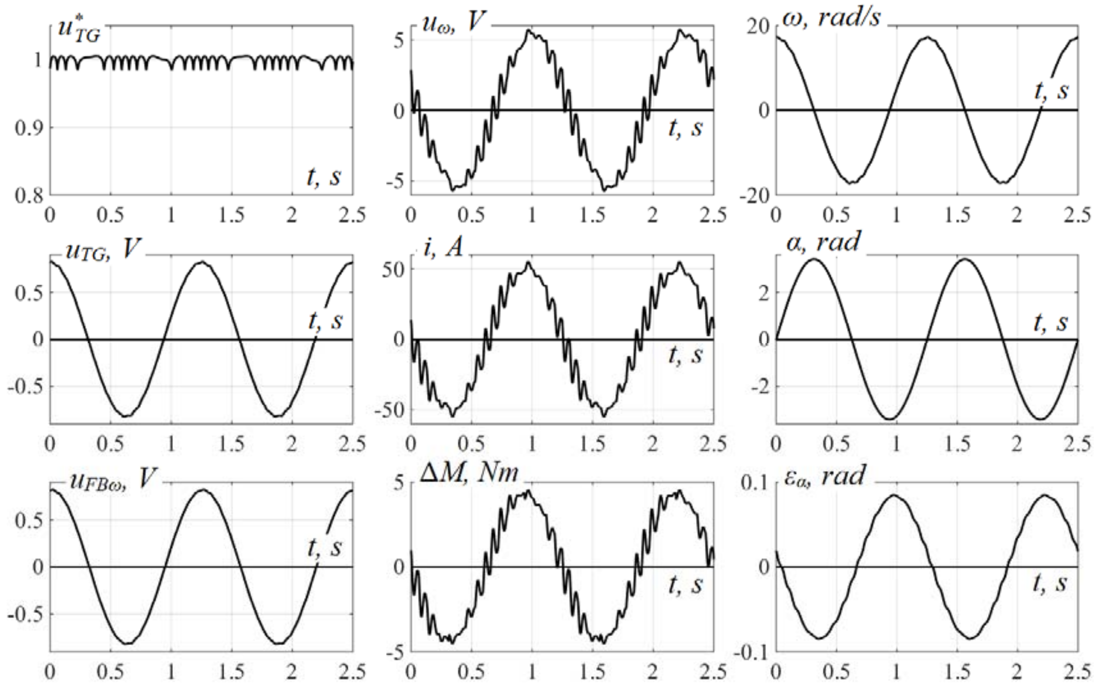

Fig. 15

As a result of the studies, families of dependences of the signal pulsation coefficients, signals pulsation swing relative values and the current effective value, as well as other indicators on the angular speed and torque of the motor were obtained. It was shown that even insignificant pulsations of the tachogenerator signal due to the relatively large value of the gain of the open angular speed control loop lead to the appearance of noticeable pulsations of other signals in the servo system. The influence of the angular speed loop damping coefficient on the system indicators was also studied. The obtained dependencies allow us to evaluate the impact of changes in the parameters of the servo system on its operating mode and make a compromise decision on the choice of values of these parameters to obtain satisfactory control quality.

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ВПЛИВ ПУЛЬСАЦІЙ СИГНАЛУ БЕЗКОНТАКТНОГО МАГНІТОЕЛЕКТРИЧНОГО ТАХОГЕНЕРАТОРА НА НАЛАШТУВАННЯ СЛІДКУЮЧОЇ СИСТЕМИ

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Розглянуто режими роботи та особливості налаштування слідкуючої системи, що містить безконтактний магнітоелектричний тахогенератор в контурі регулювання кутової швидкості виконавчого двигуна. Досліджено особливості налаштування внутрішнього контуру кутової швидкості задля компенсації електромеханічної сталої часу з урахуванням пульсацій сигналу тахогенера. Наведено залежності коефіцієнта пульсацій сигналу на виході фільтра тахогенератора, величин розмаху пульсацій сигналів у контурі кутової швидкості та діючого значення струму від параметрів режиму роботи системи. Досліджено вплив параметрів налаштування системи на показники якості регулювання кутової швидкості. Розглянуто підхід до налаштування слідкуючої системи з урахуванням параметрів контуру кутової швидкості під час забезпечення заданого запасу стійкості по фазі. Наведено результати досліджень слідкуючої системи. Бібл. 16, рис. 15, табл. 1

Ключові слова: слідкуюча система, безконтактний магнітоелектричний тахогенератор, налаштування системи автоматичного керування, запас стійкості по фазі, пульсації сигналу.

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