http://doi.org/10.35784/iapgos.2308

TAKING INTO ACCOUNT THE PHASE INSTABILITY OF GENERATORS CAUSED BY THE INFLUENCE OF IONIZING RADIATION OF SPACE ON THE PARAMETERS OF CARRIER FREQUENCY SYNCHRONIZATION SYSTEMS

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Abstract. *The article investigates the possibilities of closed and combined synchronization systems for operation in the conditions of phase instability of generators caused by the influence of ionizing radiation of outer space. The inconsistency of the closed-type synchronization system with respect to minimizing the variance of phase errors and increasing the dynamics during carrier frequency tracking is shown. For the combined synchronization system, the article clarifies the process of open communication synthesis and proposes analytical dependences that allow the technique of open communication synthesis to be specified taking into account the phase instability of generators caused by the ionizing radiation of space.*

Keywords: adjustable phase instability of the generator, ionizing radiation

ROZLICZANIE FAZY NIESTABILNOŚCI GENERATORÓW SPOWODOWANE WPŁYWEM KOSMICZNEGO PROMIENIOWANIA JONIZUJĄCEGO NA PARAMETRY SYSTEMÓW SYNCHRONIZACJI CZĘSTOTLIWOŚCI NOŚNYCH

Streszczenie. *W artykule zbadano możliwości pracy zamkniętych i kombinowanych układów synchronizacji w warunkach niestabilności fazowej generatorów spowodowanej wpływem promieniowania jonizującego przestrzeni kosmicznej. Pokazana jest niespójność systemu synchronizacji typu zamkniętego w odniesieniu do minimalizacji wariancji błędów fazowych i zwiększania dynamiki podczas śledzenia częstotliwości nośnej. Dla połączonego systemu synchronizacji w artykule wyjaśniono proces syntezy otwartej komunikacji i zaproponowano analityczne zależności pozwalające określić technikę syntezy otwartej komunikacji z uwzględnieniem niestabilności fazowej generatorów wywołanej promieniowaniem jonizującym przestrzeni.*

Słowa kluczowe: regulowana niestabilność faz generatora, promieniowanie jonizujące przestrzeni

Introduction

Phase synchronization systems are widely implemented in various radio engineering devices of communication, radar and control technology, as well as in devices of precise magnetic recording. In particular, in phase-coherent telecommunications and control systems, they are used to restore carrier and clock frequencies and for coherent demodulation of analog and digital signals with angular modulation [17].

The operation of synchronization systems is characterized by the influence of a number of disturbances and noise on their operation. Namely, additive fluctuation noise, perturbation of useful angular modulation (in the case of carrier frequency filtering), phase and frequency jumps and others. In space communication lines, for example, the main external perturbations are additive Gaussian noise and Doppler frequency shifts.

1. Formulation of the problem

Along with the external influence on the quality of the phase synchronization, the system can have internal disturbances, the main of which in phase-coherent systems are the instability of the adjustable generator [6].

In turn, one of the types of generator noise can be noise caused by the influence of one of the types of external noise, namely noise caused by the influence of ionizing space radiation (ISR) on the element base of the devices and components of communication systems [12].

The main factors of outer space that have a radiative effect on the materials and electronic equipment of space communications are [3]:

- fluxes of electrons and protons of the radiation belts of the Earth;
- streams of protons, solar cosmic rays and galactic heavy charged particles.

The effects of radiation exposure are:

- accumulation of ionization effects and structural damage in materials;
- general failures and failures of elementary electronic devices when exposed to protons and other ionizing particles of cosmic radiation.

The requirements for general stability, strength and stability of the equipment of space communication systems are determined by the integral effects in the materials of the elements under the influence of the ISR.

Short-term failures and reversible failures can be observed in the equipment due to the manifestation of ionization effects in semiconductor devices under the influence of ionizing radiation in outer space. In this case, the differential characteristics of the radiation, and the energy release density in sensitive volumes of semiconductors, are decisive.

In general, the effect of ISR on the generators of the synchronization system is manifested in the form of changes both in the conditions of the course of internal processes on which the principle of operation of these devices is based, and changes in the internal structure of the material from which they are made, which also affects the course of internal processes in them. Thus, under the influence of ionizing radiation in the generators, there is a phenomenon called the radiation effect – a change in technical characteristics under the influence of radioactive radiation.

Radiation effects lead to reversible (stationary) and irreversible (quasistable) changes in the technical characteristics of devices [5, 12].

One of the external manifestations of radiation effects in the semiconductor element base of the generator with the composition of the synchronization system is an increase in its internal noise [5].

Spacecraft synchronization systems operating under the influence of ionizing radiation of outer space must be characterized by low phase error dispersion and high speed. It is obvious that for efficient operation of the radio device as a whole, it is necessary to directly ensure high accuracy of the phase synchronization system in steady and transient modes under the influence of both external and internal perturbations [17].

The issue of determining the directions of development, analysis and improvement of known closed-type synchronization systems (CTSS) and the synthesis of new combined synchronization schemes (CSS), characterized by high noise immunity, accuracy and speed when working under the influence of both external and internal disturbances is an urgent and timely scientific task.

2. Analysis of recent research and publications

The issues of analysis of the known and the development of new schemes of phase synchronization systems, taking into account different sources of perturbations, were considered in a number of scientific works.

In [1], an algorithm for estimating phase noise based on the application of calculated coefficients of discrete discrete-cosine transformation is presented and a number of implementations of the proposed algorithm are proposed. The algorithm takes into account both the displacement of the carrier particle and phase noise, but the proposed algorithm does not take into account the assessment of the influence of internal factors, namely the instability of the generator under the influence of ISR, which adjusts to the efficiency of the synchronization system.

In [7], the results of a study of CSS with open communication under the influence of external perturbations are presented. It is noted that in contrast to simple CSS, a promising combined automatic control system in which the synthesis of open communication is offered under the condition of increasing the order of astatism has its own features due to specific input nodes of closed and open control channels. In this paper, there is no assessment of the capabilities of such a CSS to improve efficiency, taking into account the instability of the generators in the communication channel.

In [3, 10, 16], the optimization of the parameters of the filter and the system as a whole for the class of CSS is investigated. The obtained results showed that the CSS, due to their inherent contradictions, do not allow in some cases to ensure the required quality of work. This is especially noticeable when you want to improve the quality of the system on two or more conflicting indicators. The influence of generator instability under the influence of ISR in these works was not evaluated.

Great opportunities for improving the quality of synchronization systems exist in the class of CSS, which can combine the principles of regulation of deviation and perturbation, which were defined as promising areas for improving synchronization systems in [15, 17]. In [10], the importance of assessing the impact of generator instability was determined, but in it and in [1], there is no assessment of the impact of generator instability.

In such works on CSS as [4, 9], there are analyses of CSS dynamics in simple open communication consisting of the frequency discriminator (FD) and various filters (or without them), without consideration of noise both from external and from internal sources.

In [14], it was noted that the effect of generator instability can be significant. Taking it into account and minimizing it can be one of the ways to increase the efficiency of the phase synchronization system. The assessment of the impact of this instability is not described in this paper.

3. Purpose and objectives of this study

The problem of taking into account the impact of instability of generators in the communication channel caused by ISR on the efficiency of the CTSS and CSS has not been solved at present and is an urgent scientific problem, the solution of which is devoted to this article.

In the general case, the phase modulation of the signal contains four components [18]:

$$\phi_{vh}(t) = d(t) + M(t) + \Delta\psi(t) + N(t) \tag{1}$$

where: $d(t)$ – Doppler shift at the input; $M(t)$ – useful angular modulation; $\Delta\psi(t)$ – generator instability.

As noted earlier, the increase in the internal noise of the generator of the synchronization system under the influence of ISR causes a change in its operation in the direction of increasing the instability of the work [12].

Coherent reception requires accurate knowledge of the current phase of the carrier oscillation. When using the synchronization system as a phase filter, the input signal is, in accordance with expression (1) the sum $d(t)+\Delta\psi(t)$, where $\Delta\psi(t)=\psi_1(t)-\psi_2(t)$, $\psi_2(t)$ – instability of the substratum generator. Processes $M(t)$ and $N(t)$ represent a hindrance.

The variance of the phase error is caused by the instability of its operation under the influence of ISR, which consists of four components [2]:

$$\sigma_\phi^2 = \sigma_d^2 + \sigma_{\Delta\phi}^2 + \sigma_M^2 + \sigma_N^2 \tag{2}$$

The transfer function $W_3(S)$ will be:

$$\sigma_1^2 = \sigma_d^2 + \sigma_{\Delta\phi}^2 = \frac{1}{2\pi}\int_{-\infty}^{\infty}\left|W_\phi(j\omega)\right|^2 G_S(\omega)\,d\omega\,, \tag{3}$$

$$\sigma_2^2 = \sigma_M^2 + \sigma_N^2 = \frac{1}{2\pi}\int_{-\infty}^{\infty}\left|W_\phi(j\omega)\right|^2 G_n(\omega)\,d\omega\,, \tag{4}$$

where: $W(S) = 1 - W_\phi(S)$.

For this case, $G_S(\omega) = G_d(\omega) + G_{\Delta k}(\omega)$, and $G_n(\omega) = G_M(\omega) + G_N(\omega)$.

The transfer function for the error of the CTSS is defined by expression (5) [3, 10]:

$$W(S) = \frac{1}{1+W_1(S)W_2(S)W_3(S)} = \frac{T_2(S+1)S}{a_0S^2 + a_1S + a_2} = \frac{D_{\phi з0}(S)S^{\nu_з}}{F_з(S)} \tag{5}$$

hence, the transfer function $W_3(S)$ will be:

$$W_3(S) = [W_1(S)W_2(S)W_3(S)]/[1+W_1(S)W_2(S)W_3(S)] \tag{6}$$

From expressions (5) and (6), it is seen that the value can be minimized only by appropriate selection of the parameters of the links $W_1(S) - W_3(S)$.

Since these parameters are included in the characteristic CTSS equation: $F_3(S)$ = 0, changing them in order to reduce the variance of the phase error will worsen the quality of the transient process in the CTSS system [1].

Let us determine the possibilities of minimizing the variance of the phase error in CSS and the method of synthesis of open communication from the condition min σ_ϕ^2.

The block diagram of the linear model of KSS with an additional link, accepted for research, is shown in Fig. 1.

According to the transfer function for error CSS from expression (5), we find [7, 8]:

$$W_K(S) = \frac{\left[D_1(S)D_2(S)F_4(S) + F_1(S)F_2(S)D_4(S)\right]D_3(S)}{\left[F_1(S)F_2(S)F_3(S) + D_1(S)D_2(S)D_3(S)\right]F_4(S)} = \frac{D_K(S)}{F_K(S)} \tag{7}$$

where: $F_K(S) = F_3(S) \times F_4(S)$.

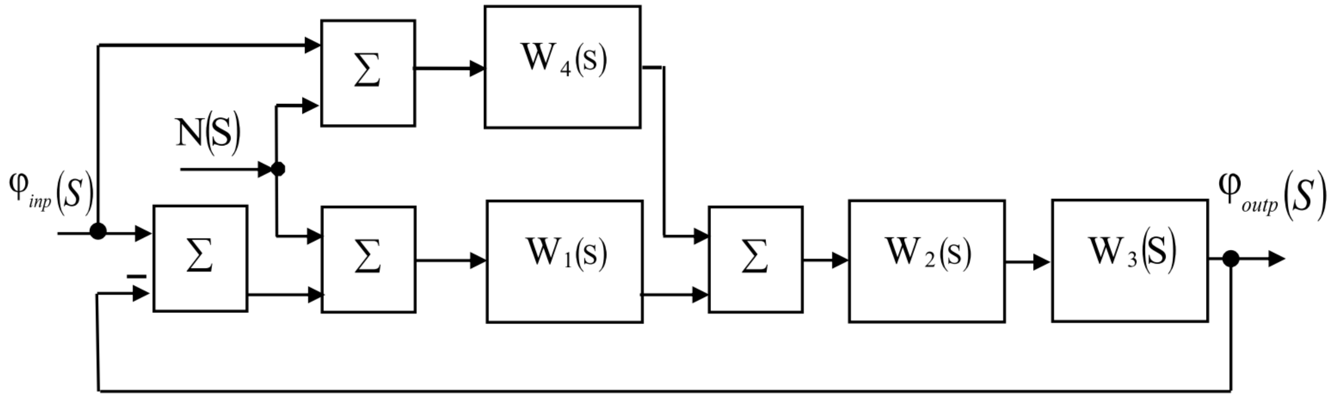

Fig. 1. Block diagram of a linear model of a combined synchronization system with an additional link

Since the numerators of the transfer functions of the KSS given by expressions (5), (7) include polynomials $F_4(S)$, and $D_4(S)$, by appropriate selection of their parameters, you can further minimize the variance of the phase error.

Taking into account that the polynomial $F_4(S)$ is included in the characteristic equation of CSS in the form of a factor, so the roots introduced by it can be chosen so that they do not affect the transient process of the initial system.

If you want the condition to be met:

$$F_4(S) = F_1(S)F_2(S), \tag{8}$$

then the transfer functions of the CSS by error and the output signal, respectively, will be:

$$W_{\phi K}(S) = \frac{F_1(S)F_4(S) + D_3(S)D_4(S)}{F_1(S)F_2(S)F_3(S) + D_1(S)D_2(S)D_3(S)} = \frac{D_{\phi K}(S)}{F_3(S)} \tag{9}$$

$$W_K(S) = \frac{\left[D_1(S)D_2(S) + D_4(S)\right]D_3(S)}{F_1(S)F_2(S)F_3(S) + D_1(S)D_2(S)D_3(S)} = \frac{D_K(S)}{F_3(S)} \tag{10}$$

In this case, the characteristic equations of the CTSS and CSS are the same, that is, $F_K(S) = F_3(S)$, the open bond can be synthesized only from the condition min σ_ϕ^2.

Consider the case of monitoring the carrier frequency against the background of noise at $d(t) = M(t) = 0$ and compare the possibilities of minimizing the variance of the phase error in the CTSS and CSS.

If you want to consider component $d(t)$, you need to consider the spectra:

$$G_S(\omega) = G_d(\omega) + G_{\Delta\varphi}(\omega),\quad G_n(\omega) = G_M(\omega) + G_N(\omega) \tag{11}$$

As is known [6, 13], the energy spectrum of instabilities of generators can be represented as:

$$G_{\Delta\phi}(\omega) = N_T + \left(2\pi N_f\right)/\left|j\omega\right|, \tag{12}$$

where N_T and N_f constants characterize the thermal noise and type noise $1/f$, respectively.

In this case, the expression for the variance of the phase error in the CTSS will be [14]:

$$\sigma_{\phi 3}^2 = \sigma_{\Delta\psi}^2 + \sigma_N^2 = \frac{r+1}{4r}\frac{N_T}{W_{L3}} + G(r)\frac{N_f}{W_{L3}^2} + \frac{N_0 W_{L3}}{2A_0^2} \tag{13}$$

where $r = \frac{A_0 K T_1^2}{T_2}$, and $W_{L3PIF} = \frac{r+1}{2T_1\left(1 + T_1/rT_2\right)}$ two-way noise band of the proportional-integrating filter (PIF) $G(r) \approx 1.5$.

From this expression, it is seen that the change of the noise band in different ways affects the value of the variance of the phase error, which is caused by the instability of the generators and additive noise.

If we take the derivative by W_{L3} and equate it to zero, we find W_{L3OPT}, the analysis of which shows that the minimum phase error dispersion is obtained by including an ideal filter (IF) in a closed loop instead of a proportional-integrating filter (PIF), which as was shown in [1], degrades the dynamics of the CTSS.

At $P_c/P = 6\cdot 10^4$, $N_T = 0$, $N_f = 0.08$ the following values will be optimal in terms of $\min\sigma_\varphi^2$: r = 7; W_{L3} = 26 Hz. Thus, we receive $G(r) = 1.6$, $\sigma_\phi = \sqrt{\sigma_\phi^2} = 1.93^\circ$.

The inclusion of an IF in the CTSS instead of a UIF slightly expands the noise band of the system [5].

$$W_{L3IF} \approx (r+1)/(2T_1)$$

and

$$W_{L3IF}/W_{L3PIF} = 1 + T_1/(rT_2) \geq 1.$$

The same increase in noise band can be obtained with a closed-loop PIF by appropriate selection of the parameters of the open channel.

Define the type and parameters of the open link, which obtains a CSS with the same band as a CTSS with an IF, but with a closed-loop PIF, the parameters of which can be selected from the condition of ensuring the required quality of system dynamics.

In other words, we will synthesize an open connection from the condition:

$$W_{LK} = W_{L3IF}, \tag{14}$$

which will optimize the system to a minimum dispersion of the phase error without deterioration of the dynamics.

In Fig. 1 $W_1(S)$ – transfer function of the phase discriminator (PD), $W_2(S)$ – filter, $W_3(S)$ – adjustable generator (AG), which have the following form [7]:

$$W_1(S)=K_1+\left(\frac{W_1(S)}{F_1(S)}\right),\ W_3(S)=\left(\frac{K_3}{S}\right)=\frac{D_3(S)}{F_3(S)} \quad (15)$$

where $K_1=A_1K_{FD}$; K_1 – gain PD; S – Laplace operator.

In the following, we will consider the systems of synchronization with the PIF in a closed loop with a transfer function of the form [8, 13]:

$$W_2(S)=\frac{(T_1S+1)}{(T_2S+1)} \quad (16)$$

The general form of the transfer function $W_4(S)$ of open communication, which satisfies the condition ν_k = l is determined by the expression [7, 8]:

$$W_4(S)=\frac{\left(\sum_{i=\nu_3}^{n}K_{4i}S^{i}\right)}{\left(\sum_{j=0}^{m}K_{4j}S^{j}\right)}=\frac{D_4(S)}{F_4(S)} \quad (17)$$

where ν_3 the order of astatism of the original system without communication.

If, in formulas (9), (10), to substitute expressions for transfer functions of links of the system of Fig. 1 of (15), (16) and (17), for n = 1, we obtain:

$$W_{\varphi K}(S)=(b_0S^2+b_1S)/(a_0S^2+a_1S+a_2)=D_{\varphi K}(S)/F_3(S) \quad (18)$$

$$W_K(S)=(C_0S+C_1)/(a_0S+a_1S+a_2)=DK(S)/F_3(S) \quad (19)$$

where $b_0=T_2$, $b_1=1-K_3K_4$, $G_1=A_0K_1K_3$, $G_0=A_0K_1T_1+K_3K_4$.

The bilateral noise band of a CSS with PIF in a closed loop will be [11, 20].

$$W_{LK}=\frac{1}{2\pi}\int_{-\infty}^{\infty}\left|W_K(j\omega)\right|^2d\omega=W_{L3I\Pi\Phi}+\Delta W_L \quad (20)$$

$$W_L=\frac{\beta^2r(K_3K_4)^2+2\beta r(K_3K_4)}{2T_1(1+\beta)} \quad (21)$$

where $\beta=T_1/(rT_2)$.

From condition (14), we find the required value of ΔW_L. Taking into account the expressions ΔW_L IF and ΔW_{L3} PIF, we have:

$$\Delta W_L=W_{L3I\Phi}-W_{L3\Pi I\Phi}=\beta(r+1)/\left[2T_1(1+\beta)\right] \quad (22)$$

Comparing expressions (21) and (22), we obtain the following equation:

$$\alpha_0(K_3K_4)^2+\alpha_1(K_3K_4)^2+\alpha_2=0, \quad (23)$$

where: $\alpha_0=\beta^2r$; $\alpha_1=2\beta r$; $\alpha_{21}=-\beta(r+1)$.

If we solve equation (23), we find the value of parameter K_4 at which the optimal transfer function CSS from the condition min σ_ϕ^2 is provided at the required quality of the system dynamics.

For the above numerical values, we have $K_4=57/K_3$.

You can increase the absolute values of the roots of the characteristic equation, for example, by increasing the value of filter parameter T_2. The noise band of the system, equal to:

$$W_{L3PIF}=\frac{r+1}{2T_1\left[1+T_1/(rT_2)\right]}=\frac{A_0K(A_0K+1)}{2\left[A_0K+1/T_2\right]}$$

will decrease, deviating from the optimal value. Therefore, the open connection must be chosen to compensate for this deviation.

Explaining expression (21), we obtain the expression for increment ΔW_L, as follows:

$$\Delta W_L=\frac{1}{2(mA_0KT_2+1)}(K_3K_4)^2+\frac{A_0K}{(mA_0K+1/T_2)}(K_3K_4) \quad (24)$$

From this expression, it is seen that at any arbitrarily small value of parameter T_2, with increasing the parameter K_4 of open communication, you can get any necessary increase in the noise band [15].

Therefore, the increase in the absolute value of the roots of the characteristic equation while maintaining the optimal value of the variance of the phase error is limited only by the physically achievable value of filter parameter T_2.

If it is also necessary to take into account the Doppler effect $(d(t)\neq 0)$, then the method of calculation of open communication remains unchanged, only in formula (3), at $G_S(\omega)$ it is necessary to substitute the sum $G_S(\omega)=G_{\Delta\phi}+G_d(\omega)$.

The Doppler shift at the input of the system is determined by a function of polynomial type [18]:

$$d(t)=\phi_0+\sum_{r=0}^{N-1}\left(\Omega_rt^{r+1}\right)\left|(r+1)\right| \quad (25)$$

If we take, for example, in the calculation of the Doppler shift (25) r =0, we will receive $G_d(\omega)=\varphi_0^2/\omega^2+\Omega_0^2/\omega^4$. Thus, taking into account the component $G_d(\omega)$ changes only the optimal value of the noise band of the CSS.

It should be noted that further promising research in the direction of solving the problem posed in this article is the solution of the problem of assessing the carrier frequency of the synchronization scheme considered in the work under conditions of exposure to ionizing radiation. In turn, the solution of scientific problems on the estimation of the carrier frequency of useful signals involves the choice of the estimation parameter and the method of their determination. As such a method of operation for signals that are transmitted in burst mode, it is proposed to use the maximum likelihood rule using a sliding fast Fourier [20]. In this case, the reference signal synchronization system itself can be improved by the open-loop synthesis method, which is described in sufficient detail in [20].

3. Conclusions

1. The paper considers the influence of the phase instability of synchronization system generators caused by the influence of ionizing radiation of outer space on minimizing the phase error dispersion in CTSS and CSS.
2. It is shown that for CTCC, minimization of the phase error variance by reducing the parameters of the transfer functions of the components of the system in the case of phase instability of the generators will worsen the quality of the transient process.
3. Increasing the noise bandwidth of the proportional-integrating filter of the input signal CTSS to the parameters of the ideal filter degrades the dynamics of this system.
4. For CSS in the conditions of phase instability of generators caused by influence of ISR, an increase in the noise bandwidth of an input signal can be achieved by applying in the closed circuit of UIF and implementation of the corresponding selection of parameters of transfer function of a link of the open channel.
5. In the conditions of phase instability of KSS generators by selection of parameters of PIF, it is possible to provide the necessary dynamics of the system and to achieve preservation of the optimum value of a variance of a phase error in it.
6. Taking into account Doppler noise in the conditions of phase instability of generators for CTSS and CSS requires a reduction of the optimal value of the noise bandwidth.
7. The analytical dependences proposed in the work allow us to specify the method of synthesis of open communication for CSS taking into account the phase instability of the generators caused by the influence of ISR against the background of the Doppler frequency shift.

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otrzymano/received: 26.09.2020 *przyjęto do druku/accepted: 10.12.2020*