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The quality of reception, as well as the processing and demodulation of the input signal in the telecommunication systems' networks, are closely related to the quality indicators in the functioning of one of the subsystems of these networks, namely a phase synchronization system. This work has directly considered the issues related to improving the performance and reducing the transitional component of the phase error generated by transition processes in the combined synchronization system. A mathematical model has been built that makes it possible to synthesize a disrupted link in the synchronization system of a telecommunication network meeting the condition for a decrease in the transitional component of the phase error. It is shown that a simple disrupted link, synthesized under the condition of suppressing a slow-fading transition component, makes it possible to shorten the time of the transition process in the system while maintaining the initial order of astatism. When a complex link is synthesized, the transition process becomes oscillatory.

It was established that under the conditions of a phase jump or a frequency jump, it is possible to improve the dynamics of the system and reduce the transitional component of the phase error variance by making the parameters for the disrupted communication link influence the roots of the characteristic equation of the transition process. The features in synthesizing disrupted communication have been considered for the intervals of movement corresponding to areas with the positive and negative inclination of the phase discriminator's static characteristic. Such conditions have been devised that make it possible to determine the value and sign of the root in the characteristic equation of the transition process, which is introduced by the parameter of a disrupted communication link separately for areas of the stable and non-steady movement of the phase discriminator's static characteristic. The reported mathematical model of disrupted link synthesis has made it possible to derive reference results. They indicated that in order to suppress the slowly fading component of the phase error characteristic equation to "0", it is necessary to provide for a significant advantage, up to 10 times, of the roots introduced by the disrupted communication link over the roots of the specified component. By changing the value for a disrupted communication parameter, one can significantly, up to 5 times or larger, shorten the time of the transition process in the combined synchronization system at a simultaneous decrease of 18–25 % in the initial value of the transition error

**Keywords:** combined synchronization system, phase error variance, phase error transitional component

# DESIGNING A SYSTEM TO SYNCHRONIZE THE INPUT SIGNAL IN A TELECOMMUNICATION NETWORK UNDER THE CONDITION FOR REDUCING A TRANSITIONAL COMPONENT OF THE PHASE ERROR

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## 1. Introduction

The process of rendering the new types of telecommunication services due to the rapid growth of traffic has predetermined a significant increase in the need for infor-

mation flows in telecommunication networks. That has led to a situation when existing telecommunication networks proved to be incapable or came to the limit of their capacity to serve subscribers at the predefined indicators of service quality.

The issue of improving the architecture of such networks and improving the quality of functioning based on the use of modern methods and principles has arisen and needs to be constantly addressed [1].

One of the directions towards improving the efficiency of computer and telecommunication networks is to increase the dynamics, which can be achieved by increasing the performance rate of input data demodulation systems, whose component is the combined phase synchronization systems. The operational effectiveness of a combined synchronization system depends, in general, on various factors of external and internal influence, as well as various restrictions [2, 3].

The issue of improving the efficiency of the phase synchronization system is a constant important scientific task. One of the directions to resolve it is to design and substantiate optimal schemes for building the system towards minimizing a phase error variance while maintaining high performance [4].

It is obvious that such schemes resolve the issue of maintaining the system's high dynamics at the predefined level of phase error variance by designing the scientifically based optimal construction schemes that function on the basis of built mathematical models. These mathematical models should take into consideration both the parameters of the components of the synchronization system construction circuit and the factors of external and internal perturbations, which was defined as a relevant scientific task in works [3–5].

It is known that one of the factors of internal disturbances and interference for a radio-electronic circuit is transient processes. They are caused by the reaction of the specified system to the transition from one stationary state to another stationary state [1, 4].

For a phase synchronization system, they may be due to cases when the input signal is received by the circuit for the first time, when the communication is interrupted, due to Doppler frequency shift, etc. [5–7].

It is determined in [3, 6] that the presence of such transient processes as one of the types of internal disturbances causes a decrease in the dynamics of the synchronization system. And the presence of additional transient oscillatory processes in the system increases the variance of the phase error by the magnitude of the transition error. Because of this, the effectiveness of the synchronization system is compromised, which has a significant impact on the operation of the entire network in general.

That requires addressing the scientific task of designing and building a phase synchronization system for the input signal, whose properties are to improve the dynamics of operation and reduce the phase error, taking into consideration the impact exerted by the transition process.

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## 2. Literature review and problem statement

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General issues of improving the performance speed of the synchronization system and minimizing the variance of the phase error by a method of the disrupted link synthesis are discussed in paper [6]. The mathematical dependences reported in the cited paper and the conclusions drawn on their basis make it possible to synthesize the complex disrupted link within the synchronization system. The paper proposes a scheme for a combined synchronization system with the predefined value of the effectiveness of its indicators, depending on the level of external additive Gaussian

noise. However, the authors do not take into consideration the internal factors and the direct impact of transitional processes that may affect the effectiveness of the application of such a scheme.

Works [8, 9] defined and substantiated the possibilities of improving the quality of synchronization systems in the class of combined synchronization systems. The cited works note that the specified systems can combine the principles of regulation for deviation and perturbation with the simultaneous provision for the minimization of phase error variance. These combinations were defined as advantages in comparison with the existing schemes to construct synchronization systems; the authors substantiated the prospects of using methods for building this type of system. In turn, the issues of taking into consideration the transition processes related to the system's reaction to incoming signal disturbances are not discussed or taken into consideration in the cited works.

Paper [10] reports the results of studying the features of the implementation of the carrier frequency recovery system in coherent signal demodulation with a continuous phase. The scheme that was given in the paper uses a phase auto-adjusting frequency system, which essentially creates open feedback in this type of combined synchronization system. The issue of practical implementation of the specified system on a modern element base is investigated in the paper. The influence of internal factors on the efficiency of such a system and the direct impact of transition processes on the type of system presented is not considered in the cited paper.

The authors of works [11, 12] proposed a method for constructing a combined synchronization system, for which they proposed an algorithm of a certain type of synchronization of a sequence of signals, which expands under the conditions of a significant excess of noise over the level of the information signal. To synchronize, one is prompted to use a utility channel that operates at the same frequency as the information channel. The distribution of channels is carried out in the formation of signals of quadratic channels: the synphase channel is used to form the phase-manipulated signal with the expansion of the spectrum, while the quadratic channel is used to transmit the clock speed signal. Taking into consideration the system's reaction to transient processes and the impact of these processes on the performance of the proposed type of synchronization system is not considered in the cited works.

Paper [13] justified and presented a direct sequence modulation scheme for distributed spectrum communication systems, which is defined as modulation of delay and addressing (DADS). The scheme reported in the cited paper is easy to implement and does not require alignment of the input code at its input, which makes it the most optimal for transmitting short signals. The cited paper did not reveal the type of scheme for which the findings were substantiated, and there are no data on assessing its performance and the influence of internal factors of this scheme and directly transition processes.

Certain considerations on the possibilities of ensuring the desired level of performance in the modified combined synchronization systems with disrupted communication are presented in paper [4]. The research was carried out in relation to one of the proposed parameters for building a synchronization system in which disrupted communication is synthesized against the background of minimizing phase error variance.

The cited paper shows that the synchronization system settings can be affected by changing the parameters for a link of its disrupted communication. The issues of influence of transition processes and other internal disturbances in the system on the effectiveness of its functioning were not considered in the cited paper.

The issue of assessing the impact of directly changing the input signal values on performance and the process of minimizing the phase error in the process of tracking the carrier frequency by the combined synchronization system of a radio communication device is considered in work [7]. In the cited work, the expediency of introducing an additional link into the disrupted communication under the conditions of influence of restrictions on any coordinate of the input signal is substantiated. It was established that the effect of introducing such a link has certain limitations, and, at certain thresholds of such restrictions, do not yield the desired effect and becomes impractical. The assessment of the impact of the transition process on the performance of the system and the issue of its reduction was not considered in the cited work.

Thus, the prerequisite for increasing the bandwidth of computer and telecommunication networks is to improve the operational efficiency of the synchronization system. That requires the development and construction of a phase synchronization system for the input signal taking into consideration the impact of the transition process on its operation in the process of tracking the carrier frequency. Such work involves researching the impact of the transition process on the operation of the synchronization system and the development of appropriate models and methods of system synthesis under the condition of reducing the defined impact.

### 3. The aim and objectives of the study

The purpose of this work is to devise a model of synthesis of the system of synchronization of the input signal of the telecommunication network, under the condition of reducing the transition component of the phase error when tracking the carrier frequency.

That would make it possible to further develop a scheme of the synchronization system, which should provide for the high dynamics under the condition of reducing the phase error when tracking the carrier frequency.

To accomplish the aim, the following tasks have been set:

- to build mathematical dependences to model the process of formation of the transitional component of the phase error in the phase synchronization system;
- to synthesize a link in the disrupted communication of the combined synchronization system under the condition of reducing the transition component of the error;
- to analyze the influence of the parameters of the synthesized link in the disrupted communication to reduce the characteristics of the transition process in the combined synchronization system;
- to substantiate the type of link in the disrupted communication of the synchronization system, if the transition component of the error is reduced and the performance of the synchronization system is improved;

- to define and form the conditions for determining the parameters for the disrupted communication link, provided that the transitional component of the phase error is reduced;
- to estimate the dependence of the transition process parameters on the parameters of the synthesized link for the disrupted communication.

## 4. The study materials and methods

This work considers the combined system of phase synchronization (CSS) in which a link for the disrupted compensatory communication is synthesized. The structural diagram of the linear model of CSS synchronization system, which is considered in our work, is shown in Fig. 1.

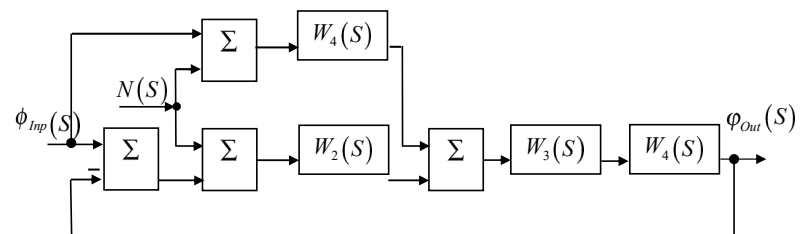


Fig. 1. Structural diagram of the linear model of the combined synchronization system with an additional link

The specified model of CSS includes an additional link with a transfer function  $W_4(S)$ , which was used to implement the disrupted link and build an open control channel [3, 5].

## 5. The study results

### 5.1. Modeling the process of forming a transitional component of the phase error of the synchronization system

In most practical cases, along with random fluctuations of the generator phase in the synchronization system, there are transient processes due to differences between phases and frequencies of input and output signals. Such a transition process occurs, for example, when the signal is received for the first time, when communication is interrupted, due to doppler frequency shift, etc. Often, these transition processes act much more strongly than the random phase oscillations.

It is known that optimizing the synchronization system to a minimum of phase error variance leads to a deterioration in its dynamics [3, 5, 7].

There are two ways to affect transition processes in the phase synchronization system [6, 14, 15]:

- reducing the time of the transition process in a single jump of the input signal phase without taking into consideration the impact of noise;
- minimizing the transitional component of the error when limiting for the variance of the main (base) error.

In case of reducing the time of the transition process in a single jump of the input signal phase without taking into consideration the influence of noise, the input signal phase is determined as  $\phi_{inp}(t)=d(t)$ , where  $d(t)$  is the harmful frequency shift at the input of the system [15].

Because the phase estimation must be accurate enough to be used in the synchronization system. Given this, the case with a high signal/noise ratio, when noise can be neglected, is of practical interest. And the estimation of system logon time in sync during the absence of noise is important in most systems related to synchronization [15, 16].

In addition, this approach makes it possible to devise a methodology for the synthesis of open communication with respect to synchronization systems, taking into consideration nonlinearity.

In order to model the process of formation of the transitional component of the phase error in the synchronization system, we determine the mathematical dependences that reveal the structure of its characteristic equation.

In the expression to determine the phase of the input signal  $\phi_{Imp}(t)$ :

$$\phi_{Imp}(t) = \phi_0 + \sum_{r=0}^{N-1} (\Omega_r t^{r+1}) / (r+1),$$

we assume  $r=0$  (phase jump) and  $r=1$  (frequency jump).

At the same time, we use the method of synthesis of open communication under the condition of suppression of slow-damping components outlined in works [3, 16, 17] regarding linear automatic control systems.

The transfer function of the phase discriminator, adopted as a link in the disrupted communication, is set in the following form:

$$W_1(S) = K_1 N(\phi), \tag{1}$$

where  $N(\phi)$  is the normalized nonlinear characteristics of the phase discriminator.

The corresponding transfer functions of the system are obtained taking into consideration the expression for the transfer function of the phase discriminator, as a link in the disrupted communication  $W_1(S) = K_1 + D_1(S) / F_1(S)$  when they include, instead of  $W_1(S)$ , its value from expression (1).

The expression to display the phase error is represented as the sum of the forced  $\phi_{fr}(t)$  and transitional  $\phi_n(t)$  components [10, 15]:

$$\phi(t) = \phi_n(t) + \phi_{fr}(t). \tag{2}$$

The forced component of the error  $\phi_{fr}(t)$  depends, in this case, on the control influence  $\phi_{Imp}(t)$  and is defined as the solution to a heterogeneous differential equation. It characterizes the accuracy of the system under a steady mode.

The transitional component of the error  $\phi_n(t)$  is the solution to the homogeneous differential equation  $F(S)\phi_n(S)=0$ . This error occurs in transition modes. The  $\phi_n(t)$  value is determined by the roots of the characteristic equation of the synchronization system.

If the characteristic equation of the synchronization system  $F(S)=0$  as a homogeneous differential equation has  $m$  simple (non-multiple) roots, then the transitional component of the error can be represented as its solution, as the sum of the exponents [6, 15]:

$$\phi_n(t) = \sum_{i=1}^m A_i e^{S_i t}, \tag{3}$$

where  $S_i$  is the  $i$ -th root of the characteristic equation,  $A_i$  is the initial value of the  $i$ -th component of the transition error.

That is, an expression was obtained that defines the parameters of the transition process as a component of its characteristic equation.

### 5. 2. Synthesizing a link in the disrupted communication of the combined synchronization system under the condition of reducing the transition component of the error

To synthesize a disrupted communication under the influence of transition processes, we refine the expression for a phase error. To this end, to switch from an expression for a phase error in the form (2) to a notation form via the time of the transition process (3), we shall use the Cauchy theorem about deductions.

Then we obtain [15]:

$$\phi(t) = \sum_{S_i} Res[\phi(S)e^{S_i t}] = \sum Res\psi(S), \tag{4}$$

where  $\psi(S) = \phi(S)e^{S_i t}$ , the deduction of the function  $f(x)$  at a special point  $a$ , which is the pole of the multiplicity  $m$ , and is determined from the expression given in [15, 16]:

$$Resf(a) = \frac{1}{(m-1)!} \left\{ \frac{d^{m-1}}{dx^{m-1}} [(x-a)^m f(x)] \right\}. \tag{5}$$

Represent the transfer function of the synchronization system and the input influence in the form of the fractional rational expressions given in [15]:

$$W_\phi(S) = \frac{\sum_{i=v}^m b_i S^i}{\sum_{i=0}^m a_i S^i} = \frac{b_m \sum_{i=v}^m (S-S_i) S^v}{a_m \sum_{i=0}^m (S-S_i)} = \frac{D_\phi(S)}{F(S)},$$

$$\phi_{Imp}(S) = \frac{\sum_{i=v}^m \beta_i S^i}{\sum_{i=0}^m \alpha_i S^i} = \frac{\beta_h \sum_{i=v}^m (S-q'_i) S^v}{\alpha_\mu \sum_{i=0}^m (S-S_q)} = \frac{M(S)}{R(S)}, \tag{6}$$

where  $S'_i, S_i, q'_i, q_i$  are the zeros and pluses of the transfer function and input influence, respectively.

Then the initial value of the  $k$ -th component of the transition component of the error, in accordance with expressions (4) and (5), at the simple roots of the equation  $F(S)=0$ , can be written in a general form as follows:

$$A_k = Res_{S=S_k} \phi(S) = \frac{b_m \beta_h \prod_{i=v}^m (S_k - S_i) \prod_{i=1}^h (S_k - q'_i)}{a_m \alpha_\mu \prod_{i=1, i \neq n}^h (S_k - q_i) \prod_{i=1}^h (S_k - q_i)} = \frac{D_\phi(S_k) M(S_k)}{F'(S_k) R(S_k)}, \tag{7}$$

where  $F/(S_k) = dF(S)/dS, S=S_k$ .

The analysis of expression (7) reveals that it is possible to equate to zero the  $k$ -th component value only when the equality  $S_k = S'_k$  is satisfied.

Synthesize the transfer functions of the links in the disrupted communication of the combined synchronization taking into consideration the input influence taking into consideration the fractional rational forms of their determination (6).

Obtain:

$$W_2(S) = \frac{B_{2l}S^l + B_{2l-1}S^{l-1} + \dots + B_{20}}{a_{2r}S^r + a_{2r-1}S^{r-1} + \dots + a_{20}} = \frac{D_2(S)}{F_2(S)}, \quad r \geq l, \quad (8)$$

$$W_3(S) = \frac{B_{3f}S^f + B_{3f-1}S^{f-1} + \dots + B_{30}}{a_{3k}S^k + a_{3k-1}S^{k-1} + \dots + a_{3v}S^v} = \frac{D_3(S)}{F_3(S)},$$

$$K \geq f.$$

Substitute expression (8) and the expression for the transfer function of the physically implemented link of the disrupted communication  $W_4(S) = D_4(S)/F_4(S)$ , min in the expression for the transfer function on the error of the combined synchronization system [15, 16]:

$$W_{\phi K}(S) = \frac{D_{\phi K}(S)S^{v_k}}{F_K(S)}.$$

Obtain:

$$W_{\phi K}(S) = \frac{b'_n S^n + b'_{n-1} S^{n-1} + \dots + b'_v S^v}{a'_n S^n + a'_{n-1} S^{n-1} + \dots + a'_0} = \frac{D_{\phi K}(S)}{F_K(S, N)}, \quad (9)$$

where  $n=r+k+m$ ,

$$F_K(S, N) = \left[ \begin{matrix} F_2(S)F_3(S) + \\ + D_2(S)K_1N(\phi)D_2(S) \end{matrix} \right] F_4(S) = F_3(S, N)F_4(S),$$

$$D_{\phi K}(S) = \left[ \begin{matrix} F_2(S)F_3(S)F_4(S) + \\ + D_2(S)D_3(S)D_4(S) \end{matrix} \right] F_1(S).$$

After expanding the expression for  $D_{\phi K}(S)$ , we find the value of its coefficients

$$\begin{aligned} b'_n &= a_{2r}a_{3k}, \\ b'_{n-1} &= a_{3r}a_{3k}T_{4m-1} + (a_{2r}a_{3k-1} + a_{2r-1}a_{3k})T_{4m}, \\ &\dots\dots\dots \\ b'_{v+1} &= (a_{21}a_{3v} + a_{20}a_{3v+1})T_{40} + \\ &+ a_{20}a_{3v}T_{41} - (b_{21}b_{30} + b_{20}b_{31}), \\ b'_v &= a_{20}a_{3v}T_{40} + b_{21}b_{30}K_{4v}. \end{aligned}$$

Thus, by synthesizing a link in the disrupted communication of the combined synchronization system with the transfer function in form (9), we derived the connection between the parameters of the link and the coefficients  $b'_n$  and  $b'_v$  in the characteristic equation of the transition process in the synchronization system.

**5.3. Analyzing the influence of parameters of the synthesized link in the disrupted communication on reducing the characteristic of the transition process in the combined synchronization system**

The analysis of expression (3) reveals that the magnitude of the transition error depends both on the roots of the characteristic equation, determining the intensity of the exponents' descent, and on the initial values of the exponents, characterizing the maximum amplitude of tran-

sition oscillation. Thus, by increasing the valid parts of the roots, or reducing the initial values of the components of the transition component of the error, one can influence its value. However, in closed synchronization systems, such possibilities are limited since the coefficients for a characteristic polynomial are selected from the condition of the compromised setting.

Let us consider and estimate the opportunities towards reducing the transition component of the phase error that the synchronization systems with combined control offer.

Expressions (8), (9), as well as their refining expressions to determine the components of the coefficients for the polynomial in the transfer function of the system for error, have been defined in this work as a model of the synthesis of the disrupted communication in the combined synchronization system, subject to a decrease in the transition component of the error.

The analysis of expressions (8), (9), and expressions for determining the coefficients for the polynomial in the transfer function of the system for error ( $D_{\phi K}(S)$ , namely,  $b'_n$  and  $b'_v$ ), reveals that the specified coefficients depend on the coefficients for the disrupted communication link  $K_{4i}$ , which are not part of the characteristic equation.

By changing the latter, one can reduce to zero the necessary basic values of the transition component of error  $A_i$  given that the coefficients  $K_{4i}$  are introduced into coefficients  $b'_j$  according to the negative sign. Thus, to reduce to zero the initial value of one component of the transition component of the error, one must introduce a derivative from the setting influence.

Moreover, the order of this derivative, in accordance with the condition for the preservation of astatism, should be equal to the order of astatism of the original system. Accordingly, to reduce  $K$  component of the transition component of the error, one must introduce  $K$  derivatives from the setting influence. The power of the polynomial  $D_4(S)$  should be  $m=k+v-1$ .

$$W_4(S) = \frac{K_{4m}S^{K+v+1} + K_{4m-1}S^{K+v-2} + \dots + K_{4v}S^v}{T_{4m}S^{K+v-1}T_{4m-1}S^{K+v-2} + \dots + T_{40}} = \frac{D_4(S)}{F_4(S)}. \quad (10)$$

After the power of the numerator  $D_4(S)$  for the operator of disrupted communication on the setting influence is determined, we find, by substituting  $W_4(S)$  in expression (9), the polynomials  $D_{\phi K}(S)$  and  $F_K(S)$ . That is, we also obtain analytical expressions for the initial values of the components of the transition component of the error.

Having equated the latter to zero (or those among the initial values of the components of the transition component of the error, which correspond to the slowly damping components and the values of the specified components must be suppressed), we obtain the following system of equations:

$$A_i = [D_{\phi K}(S_i)M(S_i)] / [F'_K(S_i)R(S_i)] = 0.$$

Solving it yields the required values for the  $D_4(S)$  polynomial coefficients.

The  $F_4(S)$  polynomial coefficients are chosen on the condition that the real part of the roots of the equation  $F_4(S)=0$  should be modulo larger than the largest root of the characteristic equation of the original system. Thus, we shall



determine the parameters for synthesizing the disrupted link for setting influence.

**5. 4. Substantiation of the type of link for the disrupted communication if the transition component of the error is reduced and the speed of the synchronization system is improved**

We shall substantiate the type of link for the disrupted communication and synthesize its parameters for the combined synchronization system. The synthesis task will be carried out under the condition for the possibility of forming an impact on the transitional component of phase error and during the transition process. These conditions should ensure an increase in the accuracy and performance of the synchronization system when monitoring the carrier frequency.

Our study considers a disrupted communication link in the form of a phase discriminator, at its triangular characteristic, and a proportionally integrating filter in a closed circuit of the synchronization system (at  $T=0$ ).

The normalized static characteristic of the phase discriminator, shown in Fig. 2, can be recorded analytically in the form borrowed from [15]:

$$N(\phi) = \begin{cases} (2/\pi)\phi + 1, & (2k-1)\pi \leq \phi \leq 2k\pi, \\ -(2/\pi)\phi + 1, & 2k\pi \leq \phi \leq (2k+1)\pi, \end{cases} \quad (11)$$

where  $K = \dots -1, 0, 1, 2 \dots$

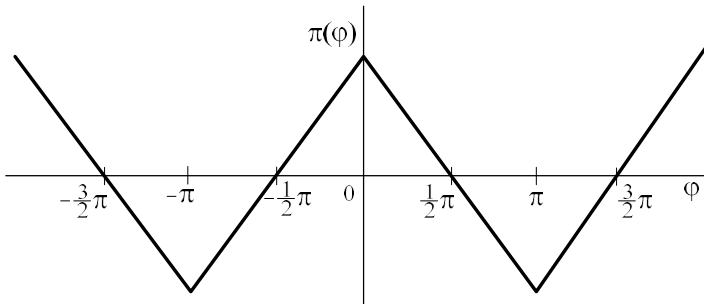


Fig. 2. The normalized static characteristics of a phase discriminator

Taking into consideration expression (11), equality (2) is transformed into two expressions describing the movement of the system at intervals  $(2k-1)\pi \leq \phi \leq 2k\pi$  and  $2k\pi \leq \phi \leq (2k+1)\pi$ , respectively:

$$\begin{aligned} \phi_1(S) &= W_{\phi 1}(S)\phi_{inp}(S), \\ \phi_2(S) &= W_{\phi 2}(S) * \phi_{inp}(S), \end{aligned} \quad (12)$$

where  $W_{\phi 1}(S)$ ,  $W_{\phi 2}(S)$  are the transfer functions for error for the corresponding intervals. Taking into consideration the functions of the transfer links, they take the following form for a closed synchronization system:

$$\begin{aligned} W_{\phi 13}(S) &= \frac{F_2(S)F_3(S)}{F_2(S)F_3(S) + D_2(S)D_3(S)K_1N_1} = \\ &= \frac{D_{\phi 13}(S)}{F_{13}(S)}, \end{aligned}$$

$$\begin{aligned} W_{\phi 23}(S) &= \frac{F_2(S)F_3(S)}{F_2(S)F_3(S) + D_2(S)D_3(S)K_1N_2} = \\ &= \frac{D_{\phi 23}(S)}{F_{23}(S)}. \end{aligned} \quad (13)$$

For a combined synchronization system

$$\begin{aligned} W_{\phi 1K}(S) &= \frac{F_2(S)F_3(S)F_4(S) - D_2(S)D_3(S)D_4(S)}{[F_2(S)F_3(S) + D_2(S)D_3(S)K_1N_1]F_4(S)} = \\ &= \frac{D_{\phi 1K}(S)}{F_{1K}(S)}, \end{aligned}$$

$$\begin{aligned} W_{\phi 2K}(S) &= \frac{F_2(S)F_3(S)F_4(S) - D_2(S)D_3(S)D_4(S)}{[F_2(S)F_3(S) + D_2(S)D_3(S)K_1N_2]F_4(S)} = \\ &= \frac{D_{\phi 2K}(S)}{F_{2K}(S)}, \end{aligned} \quad (14)$$

where  $N_1 = 2/\pi$ ,  $N_2 = 2/\pi$ .

Expanding expression (13) produces

$$\begin{aligned} W_{\phi 13}(S) &= (b_0S^2 + b_1S)/(a_0S^2 + a_1S + a_2) = \\ &= D_{\phi 13}(S)/F_{13}(S), \end{aligned}$$

$$\begin{aligned} W_{\phi 23}(S) &= (b_0S^2 + b_1S)/(a_0S^2 + a_1S + a_2) = \\ &= D_{\phi 23}(S)/F_{23}(S), \end{aligned} \quad (15)$$

where  $a_0 = b_0 = T$ ;  $a_1 = b_1 = 1$ ;  $a_2 = (2A_0K)/\pi$ .

The transition component of the error at the intervals of the constancy of the parameters in the case of simple roots will be described by the following expression

$$\begin{aligned} \phi_{13}(t) &= A_{11}e^{S_{11}t} + A_{12}e^{S_{12}t}, \\ \phi_{23}(t) &= A_{21}e^{S_{21}t} + A_{22}e^{S_{22}t}, \end{aligned} \quad (16)$$

where  $A_{ij}$  are the initial values of the exponent;  $S_{ij}$  are the roots of the characteristic equations  $F_{13}(S)$  – for the interval of the stable and  $F_{23}(S)$  – non-steady movement.

Consider first the case when there is an instantaneous jump in the phase with the value of  $\phi_j(t)$  at the input. The form of the input signal denoted through the Laplace function will be  $\phi_j(S) = \phi_j/S$ . If  $|\phi_j| > \pi/2$  then the movement to the point of stable equilibrium (in this case,  $\phi_j = -((\pi/2) + 2k\pi)$ ) will be described by both equations (16).

Over the interval of steady motion, both roots of the characteristic equation are negative, that is,  $S_{11} < 0$ ,  $S_{12} < 0$ , while  $|S_{11}| < |S_{12}|$ . To reduce the transient component of the error when the system moves in the interval  $(2k-1)\pi \leq \phi \leq 2k\pi$ , it is necessary to suppress the slow-damping component caused by the root  $S_{11}$ .

Over the interval of non-steady motion  $(2k\pi \leq \phi \leq (2k+1)\pi)$ , the roots of the characteristic equation accept different signs  $S_{21} < 0$ ,  $S_{22} < 0$ . That is, the phase error would approach the boundary of this interval  $\phi = 2k\pi$  or  $\phi = (2k+1)\pi$ . Reducing the movement time of the system in this interval can be carried out by introducing an additional rapidly in-

creasing component into the second equation of system (16). In this case, it is desirable that its initial value is maximal.

Since, in this case, there is a need to compensate (introduce) one component of the transition component of the error, the transfer function of the open channel can be derived from expression (10) at  $K=1$ . It will take the following form:

$$W_4(S) = (K_4 S) / (K_4 S \pm 1). \tag{17}$$

At the same time, for the interval of the non-steady movement, the denominator accepts a minus sign. And the root that is introduced must be positive (the process transition curve diverges from the point of the non-steady equilibrium  $\phi_{02} = \pi / 2 + 2k\pi$  to the boundary of this interval).

Substituting in expression (14) the equation of open links and expression (17) taking into consideration nonlinearity (11), we obtain:

$$W_{\phi 1K}(S) = \frac{b_{10}S^3 + b_{11}S^2 + b_{12}S}{a_{10}S^3 + a_{11}S^2 + a_{12}S + a_{13}} = \frac{D_{\phi 1K}(S)}{F_{1K}(S)},$$

$$W_{\phi 2K}(S) = \frac{b_{20}S^3 + b_{21}S^2 + b_{22}S}{a_{20}S^3 + a_{21}S^2 + a_{22}S + a_{23}} = \frac{D_{\phi 2K}(S)}{F_{2K}(S)}, \tag{18}$$

where  $a_{10}=a_{20}=a_0T_4$ ,  $a_{11}=a_1T_4+a_0$ ,  $a_{12}=a_2T_4+a_0$ ,  $a_{13}=-a_{23}=a_2$ ,  $b_{10}=b_{20}=T_2T_4$ ,  $b_{12}=1-K_3K_4$ ,  $b_{21}=T_2-T_4$ ,  $b_{22}=1-K_3K_4$ ,  $a_{21}=a_1T_4-a_0$ ,  $a_{22}=b_2T_4-a_1$ .

The law of changing the phase error for a combined system, in contrast to the closed system (16), will consist of three components:

$$\phi_{1K}(t) = B_{11}e^{S_{11}t} + B_{12}e^{S_{12}t} + B_{13}e^{S_{13}t},$$

$$\phi_{2K}(t) = B_{21}e^{S_{21}t} + B_{22}e^{S_{22}t} + B_{23}e^{S_{23}t}, \tag{19}$$

where the roots  $S_{13}=-1/T_4$ ,  $S_{23}=-1/T_4$  are introduced by additional link (17). The absolute value of the specified roots must be greater than the largest root of the original system. The initial values are determined from expressions (17), (18):

$$B_{12} = \frac{(b_{10}S_{11}^2 + b_{11}S_{12} + b_{12})\phi_i}{a_{10}(S_{12} - S_{13})(S_{12} - S_{11})},$$

$$B_{11} = \frac{(b_{10}S_{11}^2 + b_{10}S_{11} + b_{12})\phi_i}{a_{10}(S_{11} - S_{12})(S_{11} - S_{13})},$$

$$B_{13} = \frac{(b_{10}S_{13}^2 + b_{11}S_{13} + b_{12})\phi_i}{a_{10}(S_{13} - S_{11})(S_{13} - S_{12})},$$

$$B_{21} = \frac{(b_{10}S_{21}^2 + b_{21}S_{21} + b_{22})\phi_i}{a_{20}(S_{21} - S_{22})(S_{21} - S_{23})},$$

$$B_{22} = \frac{(b_{20}S_{22}^2 + b_{21}S_{22} + b_{22})\phi_i}{a_{20}(S_{22} - S_{21})(S_{22} - S_{23})},$$

$$B_{23} = \frac{(b_{20}S_{23}^2 + b_{21}S_{23} + b_{22})\phi_i}{a_{20}(S_{23} - S_{21})(S_{23} - S_{22})}. \tag{20}$$

To reduce the time of movement of the system over the interval of steady movement, it is necessary to suppress the slowly damping component, that is, the following condition must be met

$$B_{11}=0. \tag{21}$$

From this condition, we determine the value of the parameter  $K_{41}$  in the numerator of the synthesized disrupted communication.

$$K_{41} = b_{10}S_{11}^2 / K_3. \tag{22}$$

The value of the parameter  $T_{41}$  can be found from the condition  $|S_{13}| \gg |S_{12}|$ , for example,  $S_{13}=10S_{12}$ .

Then

$$T_{41} = 1 / (10S_{12}). \tag{23}$$

The expression for the transition component of the phase error will take the following form

$$\phi_{1K}(t) = B_{12}e^{S_{12}t} + B_{13}e^{S_{13}t}. \tag{24}$$

The  $B_{12}$ ,  $B_{13}$  values are obtained from (20) after the substitution of values (22), (23). Neglecting the rapidly damping component, the time of the transition process ( $t_{P1K}$ ) in this interval can be approximately estimated from the following expression:

$$t_{P1K} \approx (1/S_{12}) \ln(\pi/2B_{12}), \quad t_{P13} \approx (1/S_{11}) \ln(\pi/2A_{11}). \tag{25}$$

We shall determine parameters for an additional link for a non-steady movement interval. The value for the parameter  $T_{41}$  in the denominator is also selected from the condition  $|S_{23}| \gg |S_{21}|$ . That is, the root introduced by this link must be positive and accept a larger value than the positive root  $S_{21}$  in the initial system. For example,  $S_{23}=10S_{21}$ . Then:

$$T_{42} = 1 / (10S_{21}). \tag{26}$$

When determining values for the parameter  $K_{41}$ , we shall consider the following reasons. The roots of the characteristic equation  $F_{23}(S) = a_0S^2 + a_1S + a_1 = 0$ , describing the movement of a closed system in the interval of non-steady movement (15), will equal:

$$S_{21} = (-a_1 + \sqrt{a_1^2 - 4a_0a_2}) / (2a_0) < 0,$$

and

$$S_{22} = (-a_1 - \sqrt{a_1^2 - 4a_0a_2}) / (2a_0) < 0.$$

Given the above, the first component in expressions (16) and (19) will ascend while the second component will descend. To ensure that the difference in phases when moving over this interval is quickly gained (approaching the boundary value), it is necessary that the third component of the transition component of the error (19), introduced by the disrupted communication, should accept the sign identical to that of the first component. That is, the  $K_{42}$  parameter must be selected so that the following condition is met

$$\text{sign} B_{21} = \text{sign} B_{23} \rightarrow \max B_{23}. \tag{27}$$

If one expands expression (20), one can see that the initial values of  $B_{2i}$  are related via linear dependences to the  $K_{42}$  parameter.

**5. 5. Conditions for determining the parameters for a disrupted communication link if the transition component of the phase error is reduced**

The conditions for determining the roots  $S_{13}, S_{23}$  are as follows.

For the interval of the steady movement of the normalized static characteristic of the phase discriminator  $((2k-1)\pi \leq \phi \leq 2k\pi)$ , Fig. 2:

- it is necessary to suppress the slow-damping component, predetermined by the root  $S_{11}$  (16);
- the absolute value of the root  $S_{13}$  must accept the value of the largest root in the original system;
- to reduce the time of the transition process in the system over the interval of steady movement, it is necessary to suppress the slowly damping component under the condition of  $|S_{13}| \gg |S_{12}|$ .

For the interval of the unsteady movement of the normalized static characteristic of the phase discriminator  $(2k\pi \leq \phi \leq (2k+1)\pi)$ , Fig. 2:

- the roots of the characteristic equation must accept different signs and values by modulo, equal to  $S_{21} < 0, S_{22} < 0$ ;
- the absolute value of the root  $S_{23}$  must accept the value of the largest root in the original system;
- the root  $S_{23}$  should be positive and accept larger values than the positive root  $S_{21}$  in the initial system;
- the third component  $B_{13}$  of the transition component of error (19), introduced by the disrupted communication, must accept the sign identical to that of the first component.

**5. 6. Estimating the dependence of transition process parameters on the parameters for the synthesized disrupted communication link**

To estimate the results of synthesizing the open communication under the conditions of the influence of transient processes on the performance of the combined synchronization system, we shall model and build the dependences of the coefficients  $B_{2i}$  that are components of the roots of the characteristic equation of the transition process on the parameter  $K_{42}$  for the synthesized disrupted communication link. That is, on the parameter associated with the synthesis by the specified link of the derivative from the setting influence, the degree of which depends on the coefficient  $B_{2i}$ .

Charts of these dependences at  $K_{42} = \text{const}$  are shown in Fig. 3.

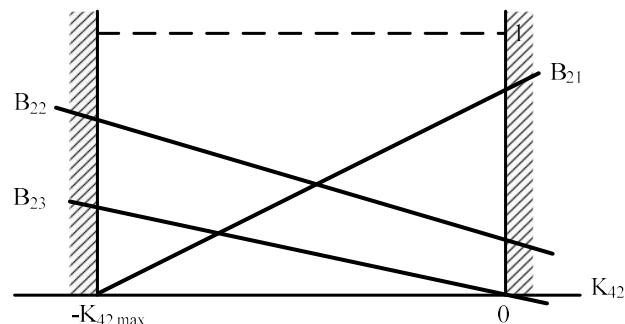


Fig. 3. Dependence chart  $B_{2i} = f(K_{42})$  at  $T_{42} = \text{const}$

When modeling, the value of  $K_{42}$  was taken as a negative derivative of the second order; its effect on the transition process described by the characteristic equation with coefficients to the second power was estimated.

In order to assess the proposed model, we synthesized the disrupted communication in the telecommunication network synchronization system under the condition for reducing the transition component of the phase error by mathematically modeling the influence of the disrupted communication link's parameters on the transition process in the system.

The modeling was carried out for the moment of a jump of the input signal phase of magnitude  $|\varphi_0| \leq \pi/2$ . That is, within the linear section of the normalized static characteristic of the phase discriminator. At modeling, we derived the law of change in the transition error  $\phi_n(t)$  dependent on the time of the transition process subject to conditions (27). Meeting which was ensured by suppressing the first component with a positive coefficient of the third component.

The roots in characteristic equation (24) of the transition error were chosen among the values determined for one of the practical implementations of the automatic phase auto-adjusting scheme [1]:

$$\phi_n(t) = -0.0394 \exp(-6.25t) + 0.0231 \exp(-4t) + 5.041 \exp(-40t).$$

At modeling, condition (27) was met; satisfying it was ensured by suppressing the first and second components with a positive coefficient of the third component associated with the parameter  $T_{41}$  of the disrupted communication link.

The corresponding dependences are shown in Fig. 4, 5.

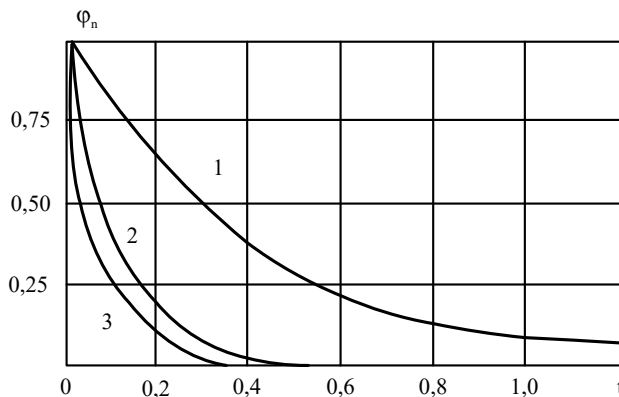


Fig. 4. Dependence of the transition process at simple roots of the characteristic equation in the synchronization system: 1 – closed type; 2 – combined type; 3 – optimal system

The dependences of the influence of the parameter  $T_{41}$  for the disrupted communication link on the transition process in the combined synchronization system are shown in Fig. 6, b. For comparison, Fig. 6, a illustrates the law of change in the transition process in the closed-type synchronization system.



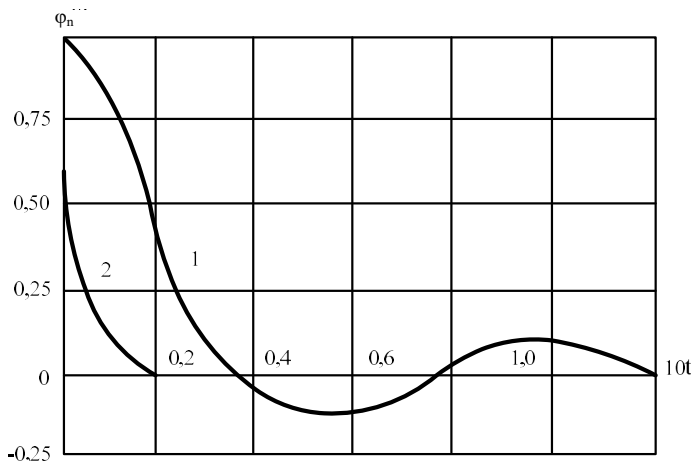


Fig. 5. Dependence of the transition process at complex roots of the characteristic equation in the synchronization system: 1 – closed type; 2 – combined type

**6. Discussion of results of synthesizing the disrupted communication, subject to an increase in the performance of the combined phase synchronization system**

Our analysis of dependences in Fig. 3 reveals that in order to satisfy the first condition (27), the  $K_{42}$  parameter must be negative, that is, one must suppress, through a sign-different value relative to the corresponding component of the characteristic equation of the transition process, the specified component to zero. To meet the second condition, it is necessary to suppress a slow-growing component.

That is, disrupted communication would ensure the maximum performance of the combined synchronization system in the interval of non-steady movement if the numerator parameter satisfies the following condition:

$$K_{42} < 0, B_{21} = 0. \tag{28}$$

From inequality  $B_{21} = 0$ , find

$$K_{42} = (b_{21} S_{21}^2 S_{21} - 1) / K_3. \tag{29}$$

Substituting  $K_{42}$  from (29) in (20), we find the initial value  $B_{22}, B_{23}$ . The expression for the transition component of the error at this interval is

$$\phi_{2K}(t) = B_{22} e^{S_{22}t} + B_{23} e^{S_{23}t}. \tag{30}$$

If the damping component is neglected, then the movement time over this interval, that is, the time of transition process damping, can be determined for the combined system ( $t_{p2K}$ ) and closed system ( $t_{p23}$ ), respectively, from the following approximated expressions (at  $\phi_{Hmax} = \pi/2$ ):

$$\begin{aligned} t_{p2K} &\approx (1 / S_{13}) \ln(\pi / 2B_{23}), \\ t_{p23} &\approx (1 / S_{21}) \ln(\pi / 2A_{21}). \end{aligned} \tag{31}$$

Equalities (25) and (31) demonstrate that the introduction of the disrupted communication with transfer function (17) makes it possible to reduce the time for movement

over both intervals in proportion to the value of the root introduced. Thus, the combined synchronization system synthesized on the condition for reducing the transition component of the error at the triangular characteristic of the phase discriminator must contain two links  $W_{41}(S), W_{42}(S)$ , and a logical device. In this case, the transition process in the system will be determined by the remaining root of the characteristic equation of the original system.

Our analysis of the dependences shown in Fig. 5 reveals that the suppression of one weakly damping component at the simple roots of the characteristic equation can significantly reduce the time of the transition process in the combined synchronization system (dependence 2) compared to the closed-type synchronization system (dependence 1). With complex roots of the characteristic equation of the closed-type synchronization system, the transition process in it would demonstrate an oscillatory character (dependence 1, Fig. 5).

The introduction of the disrupted communication link of type (17) into the system, which is synthesized under the condition of suppression of both components of the characteristic equation of a transient error, makes it possible to reduce the value of the transition error, relative to the values for the closed type system, by 18–25 %.

The transition process becomes rapidly damping by up to 3 times, compared to the time of the transition process in a closed-type system (dependence 2, Fig. 5).

The analysis of the dependences shown in Fig. 6, a reveals that the time of the transition process in the system depends on the value of the parameter of the time constant  $T_1$  for the disrupted communication link (the value of the additional root in the transfer function). In this case, the time of the transition process in the combined system can be significantly reduced in comparison with the closed-type synchronization system by varying the  $T_1$  parameter. Our estimation data show that at  $T_{42} = 0.087$  s,  $T_{42} = 0.022$  s, and  $T_{42} = 0.0087$  s the transition time in the combined system in comparison with a closed one decreases by 5.2, 6.5, and 6.7 times, respectively.

In the combined system, the synthesis of the corresponding disrupted communication can make it possible to provide for such a mode of operation when a displayed point does not extend beyond a certain area bounded by two straight lines, drawn through two adjacent points of the non-steady equilibrium parallel to the point of ordinance under the predefined initial conditions (Fig. 3). The initial conditions are accepted much larger than for a closed synchronization system.

The special features of the proposed method for synthesizing disrupted communication are taking into consideration the existence of a transition process in the synchronization system and devising methods for reducing its negative impact. Practically, this consideration is implemented in the reported mathematical model for synthesizing the disrupted communication in the synchronization system. The specified model, during synthesis, makes it possible to minimize the effect of the transition process on the parameters of the characteristic equation of the transition process in the synchronization system when tracking the carrier frequency. That was not investigated and implemented in the studies addressing the construction of promising combined systems of phase synchronization for telecommunication networks, or those tackling scientific tasks close to the material reported in the current work [8, 9, 11].

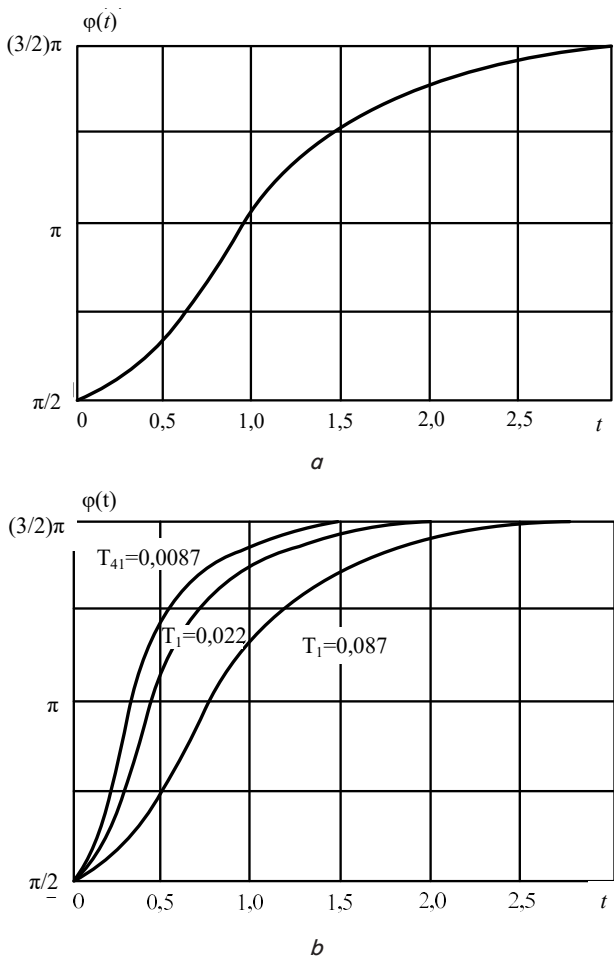


Fig. 6. Dependences of the transition process in the synchronization system: *a* – closed type; *b* – combined system, depending on the values of  $T_1$  parameter for the disrupted communication link

Further promising areas of research within the framework of resolving our scientific problem include a direct assessment of the impact of transient processes on the dynamics of the synchronization system and the development of practical recommendations for improving the dynamics of the system and accuracy in estimating the carrier frequency.

This paper considers the synthesis of simple disrupted communication, which has certain limitations to minimize the phase error. These constraints are determined by the presence of external influence in the form of additive Gaussian noise [6] and do not make it possible, in the future, to improve the accuracy of estimation of the carrier frequency and minimize the variance of the phase error [6].

The issue of influence of the additive Gaussian noise on the operation of the proposed scheme for building a synchronization system with a synthesized disrupted communication link has not been considered in the current work.

A promising area of research that could eliminate the above shortcomings and limitations may be to synthesize complex disrupted communication of the phase synchronization system, provided that the transitional component of the phase error is reduced. A link for the complex disrupted communication that could be proposed is a parallel or sequential combination of two phase discriminators. Such a combina-

tion would require additional research into the simulation of the synthesis of these disrupted communication links in the synchronization system, provided that the transitional component of the phase error is reduced against the background of the influence of additive Gaussian noise.

## 7. Conclusions

1. We have built the mathematical dependences for modeling the process that forms the transitional component of phase error in the phase synchronization system. It is determined that the value of the transition phase error depends on the initial values of the constant components and the values of roots in the characteristic equation.

2. A mathematical model has been built that makes it possible to synthesize the disrupted communication in the synchronization system of a telecommunication network under the condition of reducing the transitional component of the phase error. The model makes it possible to establish a connection between the parameters of the synthesized link and the coefficients in the characteristic equation of the transition phase error in the synchronization system.

3. We have analyzed the influence exerted by the parameters of the disrupted communication link on the parameters of the transition process in the phase synchronization system when tracking the carrier frequency. It has been established that under the conditions of phase jump or frequency jump, it is possible to improve the dynamics of the system and reduce the transitional component of phase error variance by selecting the parameters for a disrupted communication link. The selection of these parameters should imply their suppression by the values of the corresponding roots in the characteristic equation of the transition process. It has been shown that the simple disrupted communication, synthesized under the condition for suppressing a slow-fading transition component, makes it possible to shorten the time of the transition process in the system while maintaining the initial order of astatism. And, with complex disrupted communication, the transition process becomes oscillatory.

4. A phase discriminator has been substantiated as a disrupted communication link; its transfer functions have been synthesized under the condition of forming an impact on the transitional component of the phase error and on the transition process time in the synchronization system. The features in the synthesis of disrupted communication have been considered, for the intervals of movement corresponding to areas with the positive and negative inclination of the static characteristic of the phase discriminator.

5. We have established the conditions for determining the parameters of a disrupted communication link, provided that the transitional component of the phase error of the synchronization system is reduced. The modulo values and signs of the parameters for the characteristic equations of the transition process have been substantiated, influencing which could ensure shortening the time of the transition process and reducing the transitional component of the phase error. The specified conditions should be met by the parameters of a disrupted communication link in the synchronization system relative to the parameters of the characteristic equation of the transition process in it, taking into consideration the parameters of the phase discriminator for each region of the stable and non-steady movement of its static characteristic.

6. The dependence of the parameters of the characteristic equation of the transition phase error on the parameters of the synthesized disrupted communication link was estimated. It was established that in order to suppress to “0” the slowly fading component of the characteristic equation of the phase error, it is necessary to provide for a significant advantage, up to 10 times, of the roots introduced by the disrupted communication link over the roots of the specified component. In this case, the parameter of the transfer function of the disrupted communication link must accept a value up to 0.1 from the root value of the second component in the characteristic equation of the phase error, and be taken as a negative derivative of the second order. It has been shown that changing the value of the disrupted communication parameter could significantly, by up to 5 times or larger, reduce the time of the transition process in the combined synchro-

nization system at a simultaneous decrease of 18–25 % in the initial value of the transition error.

Our results have confirmed the possibilities of the proposed mathematical model to reduce the parameters of the transition process by the influence exerted by the parameters of the synthesized disrupted communication link.

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