THE METHOD FOR ANALYZING THE STABILITY OF THE PHASE FORMER OF PROBING SIGNALS OF THE ELECTRO-LOCATING INSTALLATIONS IN THE GEODYNAMIC CONTROL SYSTEMS

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Abstract: The paper notes that sensitivity and accuracy of geodynamic control can be increased by using of the phase methods of forming of the probing signals. However, this leads to a decrease in noise immunity (the influence of the multiplicative interference), as well as to the possible loss of feedback stability when registration of the geodynamic trend. It is necessary to ensure the stability of the signal formers to variations of the installation parameters and the impact of interference. It will ensure the reliability of the functioning of the phase-measuring systems of geodynamic control. The application of the generalized model of amplitude-phase formation and transformation of the signals is substantiated. This model will allow analyzing the stability of the blocks of adaptive forming of the signal in the geodynamic control systems based on multi-pole electrical installations. A new method and algorithm based on the Nyquist frequency criterion and piecewise linear hodograph approximation is developed. This algorithm is used to investigate the parametric stability of the high-order generator model. A computational experiment was performed to evaluate the stability of the formers of probing signals with different types and orders of filters. The performed verification of the calculated boundary factors of the former by the Routh-Hurwitz criterion and the D-decomposition method confirmed the correctness of the results obtained.

Key words: Phase-metric method, geodynamic control, multi-polar electrical installations, multiplicative interference, the former of probing signals, parametric stability.

1 Introduction

The use of the multi-pole electrical installations makes it possible to carry out effective geodynamic monitoring of the environment under the technogenic and climatic influence at the territories of the industrial facilities with complex buildings (H. Thunehed; Et al. 2007, Sharapov R.V., Kuzichkin O.R. 2014). The method for isolating geodynamic variations of the medium consists in analyzing the space-time variations of the electric field vectors created by a multipolar source of probing signals with a fixed position of sources and measuring bases. Tracking the geodynamics of the object is carried out by controlling of the parameters of the probing signals while simultaneously recording the phase characteristics of the field and compensating for the current trend of geoelectrical signals at the observation points (Kuzichkin O., Sharapov R. 2013).

The phase-metric method of recording of the geoelectric data is used to track the geodynamics of near-surface inhomogeneities and provides increased sensitivity to changes in the object of investigation. Practical application of this method showed its high sensitivity to weak geodynamic changes in the media under investigation and to external destabilizing factors (Dorofeev N. V., Romanov R. V., Kuzichkin O. R. 2016). The increase in the sensitivity of measurements, the initial installation and the operational positioning of the electrical installation (control of the sources of probing signals) make it possible to achieve monitoring efficiency (Dorofeev N.V., Kuzichkin O. R. 2015). However, this leads to a decrease in noise immunity (the impact of multiplicative interference), as well as to the possible loss of feedback stability when following a geodynamic trend, which is caused by external factors (temperature, humidity, etc.) (Romanov R.V. Kuzichkin O.R. 2015). During the application of this method, the cases of hardware failures were recorded at the investigation of karst processes. This were caused by the displacement of the key measurement point in the bipolar geoelectric installation and led to data loss. During the analysis of the failures, it was found that the cause of the disturbance is the appearance of a sharp change in the hydrogeological regime in the control zone. This led to a loss of system stability when the trend component of the geoelectric field vector was compensated. It is necessary to ensure the stability of the former of the probing signal when controlling the parameters of the electrical installation in various modes of measurement. This will make it possible to achieve the reliability of the functioning of the phase-measurement systems of geodynamic control. In this case, the aim of the work is to develop of the method for modeling and analyzing the parametric stability of formers of the probing signals.

1.1 The generalized model of phase formation of the probing geoelectric signals in the geodynamic control systems

When multipolar electrical installations are used in the geodynamic monitoring systems, the total probing geoelectric field is formed by controlling the phases and amplitudes of the probing signals. The probing geoelectric signals of systems can be represented by single harmonic oscillations with certain amplitudes, frequencies and phases, or a set of such oscillations. Thus, for the analysis of multipolar installations, the application of the generalized model of amplitude-phase formation and signal transformation is relevant (Kurilov, I.A., Vasiliev G.S., Kharchuk S.M. 2010). The model will simplify the design of geodynamic control systems, as well as provide an opportunity to assess the extreme conditions of their operation.

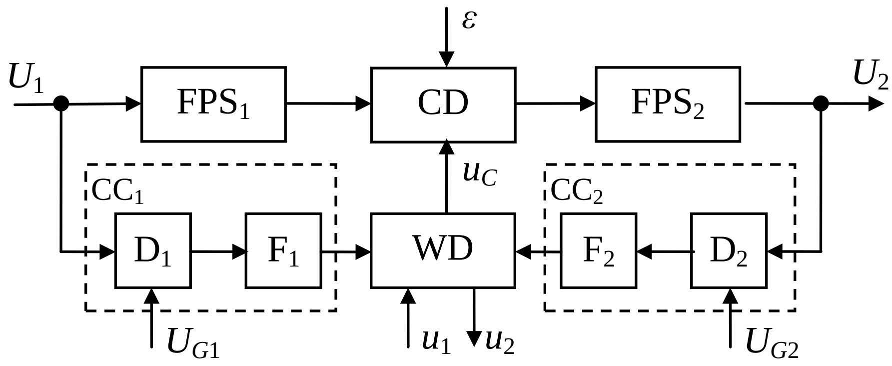


Figure 1: The generalized model of the amplitude-phase former of the probing signals. Designations: $U_{1,2}$ are the main input and output signals of the *FZS*, $U_{G1,2}$ are the signals of equivalent reference generators of detectors ($D_{1,2}$), *F's* are the filters in the detection circuit, $u_{1,2}$ are the auxiliary input and output signals, u_C is the control signal, ε is the destabilizing factor.

The generalized model of the former of the probing signal (FPS) presented in Figure 1 is identical to the model described in (Vasilyev G.S., Kurilov I.A., Kuzichkin O.R., Surzhik D.I., Kharchuk S.M. 2015). The model consists of two similar formers of probing signals FPS $_{1,2}$, control device (CD), control channels ($CC_{1,2}$) and a weight distributor (WD). The amplitude and (or) phase of the input signal of the former are controlled in the CD. The channels CC_1 and CC_2 consist of the detector for deviating the amplitude and / or phase of the signal, as well as the filter. The $CC_{1,2}$ channels realize the principle of regulation by perturbation and deviation, respectively. The values of the transmission factors WD determine the proportions of the transmission of signals from its inputs to the outputs, on the basis of which the control and output auxiliary signals FPS are formed.

The different variants of the construction of the former - with regulation by disturbance (RD), deviation (RDev) and combined control (CC) can be obtained by selecting the values of the corresponding weight distributor coefficients. Further disclosure of $FPS_{1,2}$ allows to represent devices of different types (direct, reverse, local, common, multi-loop) and its number of connections. Thus, the flexible structure of the generalized model makes it possible to investigate a wide class of circuitry of the formers of the signal of electro-locating devices that differ in the number of channels (poles), the dependence between the signal parameters in individual channels, the characteristics of the links, the magnitude of the disturbances and possible changes in the control object.

1.2 Analysis of the parametric stability of the former of the signal of electro-locating installations on the basis of the generalized model

The urgency of the problem of analyzing of the parametric stability is determined by the need to maintain the balance of the probing device for its successful operation with a variation in the parameters of the installation and the impact of small and large noise. For the study of parametric stability, it is proposed to use the combined approach based on the Nyquist frequency criterion, the D-partitioning over a set of parameters, and the piecewise linear hodograph approximation (Zaitsev, G.F. 1978).

The proposed method on the basis of the generalized FPS model with the use of approximation by continuous piecewise linear functions (Kuzichkin O.R., Bykov A.A., Kurilov I.A.2015) makes it possible to analyze the parametric stability of high-order of the FPS in the wide range of circuit parameters and interference impact.

From the theory of automatic control, it is known that the including of a coupling according to the determining influence does not affect the stability of the device, i.e. in the combined systems, the stability conditions are determined only by the characteristic equation of the closed part (Gonorovsky, I.S. 1971). Equating to zero the denominator of the operator transfer coefficient-the characteristic polynomial the characteristic equation is obtained:

$$1 + N_2 M_2(p) = 0 \tag{1}$$

where N_2 is the coefficient of regulation of the chain, $M_2(p)$ is the transmission coefficient F_2, $p = d/dt$ is the Laplace operator.

The device is stable (Postnikov, M.M. 1981, Gryazina, E. N. 2008), if all the roots of equation (1) have a negative real part. If there is at least one imaginary root in the equation (1), the FPS is at the stability boundary, while the real parts of the other roots must be negative.

Thus, taking the $(p = j\omega)$ in (1), the value of the coefficient N_2 corresponding to the stability boundary will be determined by the formula:

$$N_2(\omega) = \mathrm{Re}[N_2(\omega)] + j\,\mathrm{Im}[N_2(\omega)] = -\frac{1}{M_2(j\omega)}. \tag{2}$$

The arbitrary value of the frequency corresponds to a complex value. Since the coefficient N_2 is the real number, the condition for the stability boundary of the former will take the form $\mathrm{Im}[N_2(\omega)] = 0$. According to (2), this condition is satisfied if:

$$\mathrm{Im}[M_2(j\omega_k)] = 0 \tag{3}$$

where ω_k are the critical frequencies (the root values corresponding to the stability boundary), k is the root number.

For the arbitrary configuration and order F_2, its complex transfer coefficient can be conveniently represented in the form (Vasilyev G.S., Kurilov I.A., Kharchuk S.M. 2013)

$$M_2(j\omega) = \frac{\sum_{i=0}^{I} \alpha_i (j\omega)^i}{\sum_{i=0}^{I} \beta_i (j\omega)^i} \tag{4}$$

where I is the order of the filter, α_i, β_i are the filter coefficients.

The formula (4) in a general form for different filter coefficients in the feedback loop α_i, β_i must be transformed. To do this, in the numerator and denominator of the complex transfer function the real and imaginary parts must be transformed by the formulas:

$$A_{1i}(\omega) = \mathrm{Re}[A_i(j\omega)] = \alpha_{4i}\omega^{4i} - \beta_{4i+2}\omega^{4i+2}$$

$$B_{1i}(\omega) = \mathrm{Re}[B_i(j\omega)] = \beta_{4i}\omega^{4i} - \beta_{4i+2}\omega^{4i+2}$$

$$A_{2i}(\omega) = \mathrm{Im}[A_i(j\omega)] = \alpha_{4i+1}\omega^{4i+1} - \alpha_{4i+3}\omega^{4i+3} \tag{5}$$

$$B_{2i}(\omega) = \mathrm{Im}[B_i(j\omega)] = \beta_{4i+1}\omega^{4i+1} - \beta_{4i+3}\omega^{4i+3}.$$

Then (4) taking into account (5) takes the form

$$M_2(j\omega) = \frac{\sum_{i=0}^{I}[A_{1i}(\omega) + jA_{2i}(\omega)]}{\sum_{i=0}^{I}[B_{1i}(\omega) + jB_{2i}(\omega)]} = \frac{A_1(\omega) + jA_2(\omega)}{B_1(\omega) + jB_2(\omega)}. \tag{6}$$

After the conversion, the formulas will be received

$$\left(\sum_{i=0}^{I} \alpha_{4i+1}\omega_k^{4i+1} - \alpha_{4i+3}\omega_k^{4i+3}\right) \times \left(\sum_{i=0}^{I} \beta_{4i}\omega_k^{4i} - \beta_{4i+2}\omega_k^{4i+2}\right) - \\ - \left(\sum_{i=0}^{I} \alpha_{4i}\omega_k^{4i} - \beta_{4i+2}\omega_k^{4i+2}\right) \times \left(\sum_{i=0}^{I} \beta_{4i+1}\omega_k^{4i+1} - \beta_{4i+3}\omega_k^{4i+3}\right) = 0. \tag{7}$$

Here, the filter coefficients are defined by zeros: $\alpha_{i>I}$, $\beta_{i>I}$=0.

The roots of the equation (7) correspond to the boundary values $N2(\omega)$ in formula (5). To find the roots it is necessary to designate the left-hand side of equation (7) as the function of $f(\omega)$. The order of the polynomial $f(\omega)$ is equal to the order of the filter F_2 and is equal to I. The general solution of the polynomial of arbitrary order is absent. Next, it is necessary to approximate $f(\omega)$ on the basis of the continuous piecewise functions (CPF) (Kurilov I.A., Vasiliev G.S., Kharchuk S.M., Surzhik D.I. 2012). This allows determining the roots of the equation with any given accuracy for any order of F_2. Defining of the approximation parameters: the range of the variable from ω_0 to ω_N, N is the maximum number of the approximation node, Δ_ω is the step of the variable change, and n is the current number of the approximation node. The CPF approximating the polynomial $f(\omega)$ in the interval $(\omega_0; \omega_N)$ takes the form:

$$f_\Sigma(\omega) = \sum_{n=0}^{N-1} f_n(\omega) Q_n(\omega) \tag{8}$$

where $f_n(\omega) = K_n\omega + L_n$ – is the straight line approximating of the $f(\omega)$ on the section $\omega_n \div \omega_{n+1}$, $K_n = \left[f(\omega_{n+1}) - f(\omega_n)\right] / \Delta_\omega$, $L_n = f(\omega_n) - K_n\omega_n$ are the approximation coefficients, $\Delta_\omega = (\omega_N - \omega_0)/N$ and

$$Q_n(\omega) = \frac{1}{2\Delta} \sum_{\lambda=0}^{1} \sum_{\gamma=0}^{1} (-1)^{\lambda+\gamma} \left|\omega - \omega_n - \gamma\Delta_\omega + \Delta(1-\lambda)\right|$$

are the CPF inclusive, forming of the approximate section of the line, Δ is the arbitrary small number, λ, γ – are the coefficients equal to "0" or "1".

The roots (8) are defined as the intersection points of the approximating lines $f_n(\omega)$ with the abscissa axis, that is $f_n(\tilde{\omega}_{kn}) = 0$:

$$\tilde{\omega}_{kn} = -L_n / K_n . \tag{9}$$

As a result, getting N roots. To exclude "false" roots $\tilde{\omega}_{kn}$, it suffices to multiply (9) by $Q_n(\tilde{\omega}_{kn})$:

$$\omega_{kn} = \tilde{\omega}_{kn} Q_n(\tilde{\omega}_{kn}) . \tag{10}$$

The corresponding inclusion function from the "false" roots is zero. The boundary values N_{2k} for each true root are obtained by substituting the nonzero values (10) into (2)

$$N_{2k} = N_2(\omega_k) = -\frac{1}{M_2(j\omega_k)} \tag{11}$$

Taking (4) into account, obtaining:

$$N_{2k} = -\frac{1}{M_2(j\omega_k)} = -\frac{\sum_{i=0}^{I} \beta_i (j\omega_k)^i}{\sum_{i=0}^{I} \alpha_i (j\omega_k)^i} \tag{12}$$

In accordance with formula (12), the values are real. Omitting the imaginary component, the formula (12) takes the form:

$$N_{2k} = -\frac{\left(\sum_{i=0}^{I} \alpha_{4i}\omega_k^{4i} - \beta_{4i+2}\omega_k^{4i+2}\right) \times \left(\sum_{i=0}^{I} \beta_{4i+2}\omega_k^{4i+2} - \beta_{4i}\omega_k^{4i}\right)}{\left(\sum_{i=0}^{I} \alpha_{4i}\omega_k^{4i} - \beta_{4i+2}\omega_k^{4i+2}\right)^2 +} \rightarrow$$

$$\rightarrow \frac{\left(\sum_{i=0}^{I} \alpha_{4i+1}\omega_k^{4i+1} - \alpha_{4i+3}\omega_k^{4i+3}\right) \times \left(\sum_{i=0}^{I} \beta_{4i+3}\omega_k^{4i+3} - \beta_{4i+1}\omega_k^{4i+1}\right)}{+\left(\sum_{i=0}^{I} \alpha_{4i+1}\omega_k^{4i+1} - \alpha_{4i+3}\omega_k^{4i+3}\right)^2} . \tag{13}$$

The joint solution of the equations (7) and (13) allows obtaining the values of all the boundary coefficients of the former with arbitrary filters. To analyze the stability of a particular version of the FPS, it is necessary to perform the substitution of the filter coefficients F_2 (α_i, β_i) in these formulas. The total number of the boundary coefficients is determined by the order of equation (7) and is equal to the order of the filter I.

The results of the computational experiment on the analysis of the stability of the FPS operation with the different types of the filters

As an example, we calculate the area of stable work of the former, when the F_2 filter is a 5th order low-pass filter with a transfer function (Popov, P.A. 1998) $M_2(p) = 1/(1+Tp)^5$, where T is the filter time constant. The coefficients F_2 take the values:

$$\alpha_0=1,\ \alpha_{1\div5}=0,\ \beta_0=1,\ \beta_1=5T,\ \beta_2=10T^2,\ \beta_3=10T^3,\ \beta_4=5T^4,\ \beta_5=T^5. \tag{14}$$

Substituting the values of the coefficients in the formulas (5) and (6), obtaining:

$$A_1(\omega)=1,\ A_2(\omega)=0,\ B_1(\omega)=5T^4\omega^4 - 10T^2\omega^2 - 1,$$

$$B_2(\omega)=T^5\omega^5 - 10T^3\omega^3 + 5T\omega. \tag{15}$$

The polynomial of the left-hand side of equation (7) takes the form:

$$f(\omega) = -T^5\omega^5 + 10T^3\omega^3 - 5T\omega. \tag{16}$$

Taking the time constant T=1c and approximating of the polynomial (8) in the range of variables $\omega_0 = 0c^{-1}$, $\omega_N = 4\,c^{-1}$, N=100, $\Delta_\omega = 0{,}04\,c^{-1}$. From all N=100 roots (9) to define the true roots: $\omega_0 = -3{,}078c^{-1}$, $\omega_1 = -0{,}727c^{-1}$, $\omega_2 = 0$, $\omega_3 = 0{,}727c^{-1}$, $\omega_4 = 3{,}078c^{-1}$. The values N_{2k} corresponding to the roots (13) are equal to $N_{20} = -354{,}885$, $N_{21} = 2{,}885$, $N_{22} = -1$, $N_{23} = 2{,}885$, $N_{24} = -354{,}885$. Defining the $N_2^{н} = -1$, $N_2^{в} = 2{,}885$. Consequently, the stability region of the former with the low-pass filter of fifth-order in the CC_2 represents the section $-1 \le N_2 \le 2{,}885$. The result coincides with the D-decomposition method obtained in (Gryazin, E.N. 2004).

Analogously, carrying analyze of the stability of the FPS with filters of other types and orders. Let's calculate the area of stable operation of the converter with four types of filters in the RDev circuit: low-pass (LPF), high-frequency (HPF), bandpass (BF) and rejection (RF). LPF and HPF are of the order up to and including the 10th (*I = 1 ... 10*), for BF and RF at *I = 2,4,6,8,10*. Each LPF and HPF consists of the same filters of the first order. The composition of the BF and RF includes the equal number of links of the low-pass filters and high-pass filters of the first order.

The transfer functions of the filters are:

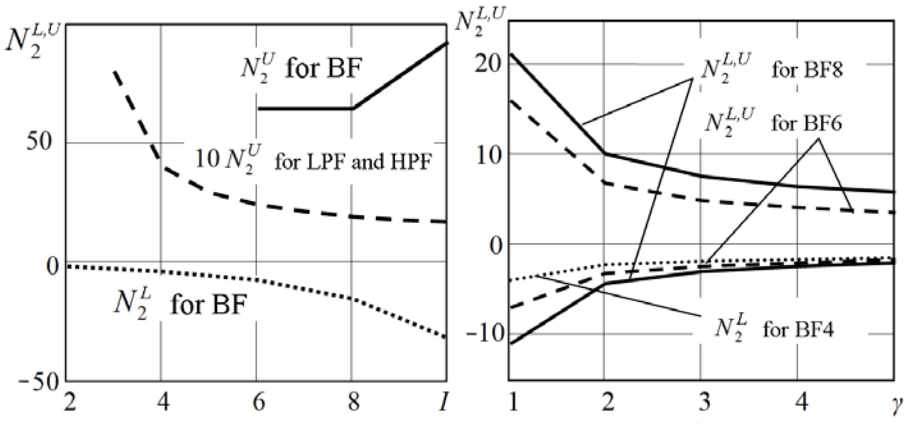
$$M_2^{\mathrm{LPF}}(p) = 1/(1+Tp)^{\mathrm{I}}$$

$$M_2^{\mathrm{HPF}}(p) = (Tp)^I/(1+Tp)^I$$

$$M_2^{П\Phi}(p) = \mathrm{H}_{\mathrm{LPF}}(\mathrm{p})\mathrm{H}_{\mathrm{HPF}}(\mathrm{p}) = (\gamma Tp)^{0.5I}/[(1+Tp)(1+\gamma Tp)]^{0.5I} \quad (17)$$

$$M_2^{\mathrm{RF}}(p) = 1 - M_2^{\mathrm{BF}}(p)$$

In the formulas 17, *T* is the time constant of the link in the LPF and HPF, γ is the ratio of the time constants of the HPH and LPF links in the composition of the BF and RF. The coefficients F_2 are determined from the formula of the transfer function for a particular type and order of the filter. The polynomial of the left-hand side of (7) is obtained with allowance for (5) for the found values of the coefficients. The obtained dependences $N_2^{н,в}$ are shown in Fig. 2.



a)   b)

Figure 2: The boundary values of the stable transmission coefficients of feedback circuits for devices with different types of filters: a) the dependence on the order of the filter *I*; b) the dependence on the parameter *γ*

The lower bound $N_2^{L,U} = -1$ for any order of the LPF and the HPF is not shown in the figure. For these types of the filters for *I=1* and *I=2*, the upper limit values are not ($N_2^U \to \infty$), the FPS with LPF and with HPF is stable at values are $N_2 \geq -1$. As the order of F_2 increases, the stability area narrows from above (N_2^U is decreases).

The area of stability of the FPS with the BF for *γ = 1* has a different character (Fig. 2a). For values of *I=1* and *I=2*, the upper limit is absent ($N_2^U \to \infty$). With an increase in the order of the BF, the stability area expands both from above and from below.

The areas of stability of the FPS with the BF of different orders for the values of *γ=1÷5* are shown in Fig. 2b. As can be seen from the figure, with increasing *γ* and any order of the BF, the stability area narrows both from above and from below. For the RF N_2^L weakly depends on the filter order for any *γ*, approximate value is $N_2^L \approx -1$, upper limit is $N_2^U \to \infty$ (not shown in the figure).

The Raus-Hurwitz test for the various fixed values $N_2 = N_{2k}^*$ was performed for each filter under study. The verification confirmed the stability of the converter in the main section $[N_2^L; N_2^U]$ and the instability in all others $[N_{2\,k}; N_{2\,k+1}]$.

2 Conclusion

The application of the generalized model of amplitude-phase formation and transformation of the signals is substantiated. This model will allow analyzing the stability of the blocks of adaptive forming of the signal in the geodynamic control systems based on multi-pole electrical installations.

Application of the model will simplify the design of geodynamic control systems, as well as provide an opportunity to assess the extreme conditions of their operation. The method for analyzing the stability of high-order formers with different types of control channel filters has been developed. The new approach is based on the use of the Nyquist frequency criterion and piecewise linear approximation of the hodograph of the transfer function of the former. The choice of the specific filter of the control path is carried out by simply substituting its coefficients in the obtained formulas of the generalized FPS model.

A computational experiment was performed to evaluate the stability of the formers of probing signals with different types and orders of filters: with filters of low frequencies, high frequencies, band and notch filters from 1 to 10 order. The performed verification of the calculated boundary factors of the former by the Routh-Hurwitz criterion and the D-decomposition method confirmed the correctness of the results obtained. In contrast to the Routh-Hurwitz criterion, in order to study the parametric stability of the FZS, the developed method does not require solving the system of inequalities. The construction of a hodograph or boundary curves is also not required.

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