International Journal of Advanced Science and Technology
Vol. 29, No. 11s, (2020), pp. 218-227

The phase-metric method of isolating the information component in the distributed processing of geoelectric signals in geoecological monitoring systems

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Abstract

The article discusses the principles of isolation of the phase information component based on the results of processing analog signals in geoecological monitoring systems operating in agricultural development zones of the territories. The features of using geoelectr%%ic methods are shown, the disadvantages of traditional approaches for estimating the amplitudes of recorded signals are indicated. The use of a method based on monitoring the phase dynamics of the recorded geoelectric signals coming from pairs of receiving lines of grounding electrodes is proposed. A generalized block diagram of the receiving path of the phase monitoring system and options for its adaptation to the processing of recorded analog signals are presented. The structural blocks and functional models of this generalized scheme are determined, and a mathematical description of all stages of processing the input geoelectric signals of the receiving path of the phase monitoring system is given, justifying the effectiveness and feasibility of the proposed approach. To test it, experimental studies of the layout of the phasometric measuring system for monitoring geodynamic karst processes in the coastal zone of Lake Svyato, Nizhny Novgorod Region were performed, which showed its high sensitivity and potential for solving problems of detecting, localizing and predicting small geodynamic events.

Ke words: *agro-industrial complex, geoecological monitoring, geoelectrics, phase-metric method.*

1. Introduction

Geoecological monitoring [1-3] is widely used for monitoring and control the impact of geoecological processes in the zones of development of the territories by the agro-industrial complex [4,5] on natural resources and infrastructural engineering and technical objects in the process of their interaction. It is a system of continuous instrumental measurements and forecast estimates in accordance with certain methods. Its application allows to obtain the information necessary for monitoring and evaluating adverse natural and technological processes, calculate the predicted characteristics of the geoecological stability of the territory, and also develop recommendations for making operational management decisions for its conservation.

Modern systems of complex geoecological monitoring are complex software and hardware complexes [3], consisting of many heterogeneous highly sensitive spatially separated recording devices (sensors, communication equipment, etc.); analog and digital signal processing paths; storage, transmission and display devices; as well as the software necessary for their joint work.

One of the options for the implementation of geoecological monitoring is the use of modern systems based on the use of geoelectrical control methods [6-11], the active use of which is due to the high geoecological sensitivity of the electrical properties of the controlled objects [11]. Among these properties, it can be noted electrical resistance, dielectric constant, polarizability, absorption, electrochemical activity and many others. The principles of application of active geoelectric methods are based on the study of monitoring objects using artificial sources of electric fields [6-11] formed by point feed (emitting) grounding electrodes. Wherein, for the implementation of distributed registration of geoelectric signals, as a rule, multi-pole receiving paths of geoelectric monitoring systems are used (formed by a network of point receiving electrodes-earthing, placed in one or another spatial configuration, depending on the nature of the tasks to be solved for a particular monitoring object) and hardware and software for processing recorded geoelectric signals.

The main drawback of traditional approaches to geoelectric monitoring is the fact that in the vast majority of cases they belong to the class of amplitude methods [9, 10], the main disadvantage of which is the difficulty in solving monitoring tasks in the presence of regular interference effects, changes in climatic factors and variations in the parameters of a particular installation (for example, when changing the spatial arrangement of the sensors, reducing the sensitivity of the receiving electrodes due to their oxidation, etc.). The consequence of this problem is a decrease in the sensitivity (and, accordingly, efficiency) of geoelectric methods, to increase which it is necessary to apply special measures to ensure accurate adjustment of input signal levels, compensation of existing interference of natural and artificial origin, as well as the use of calibration procedures when changing parameters of geoelectric installations.

The use of noise-resistant approaches to the development of geoecological monitoring systems using geoelectric monitoring methods, the informative parameter of which is not the amplitude but the phase characteristics of the recorded signals, seems to be promising in this aspect.

2. Phase-metric geoelectric method of geoecological monitoring

One of the options for increasing the geodynamic sensitivity during geoecological monitoring is the use of the phase-metric method [12-17], the idea of which is applied to the problem under consideration is based on tracking the dynamics of changes in the phases of the recorded geoelectric signals relative to the phase of the reference highly stable oscillation. Wherein, for the formation of a geoelectric field of a given configuration and with specified parameters, several emitting point sources located in a controlled area are used, and for reception, the required number of pairs of point meters are used. Point sources form probing signals that are phase shifted by a given angle relative to each other. Geodynamic variations of the medium are determined by the displacement of fictitious sources, which lead to an imbalance of the measuring system and registration of the corresponding vector of signal in it.

In general case, the principle of phase-metric monitoring for an arbitrary receiving line of a geoecological monitoring system can be depicted as the block diagram shown in Figure 1, where the following notation is adopted: PCD - phase comparison device, IDIC - isolation device of information component, PID - phase isolation device.

Figure 1. Generalized block diagram of the receiving path of the phase-metric monitoring system

In this scheme, the phase comparison device is a mismatch sensor, the output signal of which contains a component proportional to the phase difference of two input signals: information from one of the receiving lines of the geoecological monitoring system and reference from the reference generator. For isolating this component from the additive signal-noise mixture of the output signal of the phase comparison device, in the generalized circuit is used a isolation device of information component, the output signal of which is directly converted to the phase signal in the phase isolation device.

In the simplest case, to implement the phase-metric method of geoecological monitoring, one pair of receiving grounding electrodes *MN* and one pair of probing grounding electrodes *AB* can be used, for which probing quadrature harmonic signals $s_A(t)$ and $s_B(t)$ are described as

$$s_A(t) = U\,sin(wt),$$

$$s_B(t) = U\,sin\left(wt + \frac{\pi}{2}\right) = U\,cos(wt), \tag{1}$$

where U is the voltage amplitude, w is the circular frequency, t is time.

In the absence of interference acting on the receiving grounding electrodes, the signals from each of them with single amplitudes are defined as

$$s_M(t) = sin\left(wt + \varphi_M + \Delta\varphi_M(t)\right),\ s_N(t) = sin\left(wt + \varphi_N + \Delta\varphi_N(t)\right), \tag{2}$$

where φ_M and φ_N are the trend components of the phases from each receiving electrode, $\Delta\varphi_M(t)$ and $\Delta\varphi_N(t)$ are the dynamic components of the phases from each receiving electrode.

3. Application of the phase-metric method for isolating informative signals in geoecological monitoring

To isolating the information signal, it is necessary to form a signal containing data on the dynamics of the phase between the receiving grounding electrodes. Such information may be contained in a difference signal is described as

$$s_{DA}(t) = s_M(t) - s_N(t), \tag{3}$$

and is obtained, for example, by hardware at the output of an ideal differential amplifier, the functional diagram of which is shown in Figure 2.

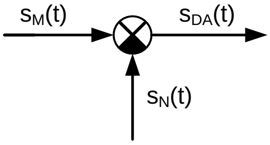


Figure 2. Functional model of an ideal differential amplifier

Taking into account the transformation (1-3), obtain the following output signal of an ideal differential amplifier

$$s_{DA}(t) = 2\sin\left[\frac{\varphi_M + \Delta\varphi_M(t) - \varphi_N - \Delta\varphi_N(t)}{2}\right]\cos\left[wt + \frac{\varphi_M + \Delta\varphi_M(t) + \varphi_N + \Delta\varphi_N(t)}{2}\right], \tag{4}$$

which, based on this expression, is an amplitude-phase modulated signal, which, for brevity, can be written as

$$s_{DA}(t) = U_{DA}(t)\cos\left[wt + \varphi_{MN} + \Delta\varphi_{MN}(t)\right],$$

where $U_{DA}(t) = 2\sin\left[\frac{\varphi_M + \Delta\varphi_M(t) - \varphi_N - \Delta\varphi_N(t)}{2}\right]$ is the law of amplitude variation of the output signal of an ideal differential amplifier, $\varphi_{MN} = \frac{\varphi_M + \varphi_N}{2}$, $\Delta\varphi_{MN}(t) = \frac{\Delta\varphi_M(t) + \Delta\varphi_N(t)}{2}$.

In cases where it is necessary to take into account the presence of a the interference component at each input of the differential amplifier, which is additively added to the useful signal, as well as the non-ideal amplifier to attenuate the common-mode input signal, the functional model of the device can be depicted in the form shown in Figure 3. Coefficient *K1* in this model takes values close to 1 and takes into account the final value of the attenuation coefficient of the common-mode signal of a real differential amplifier.

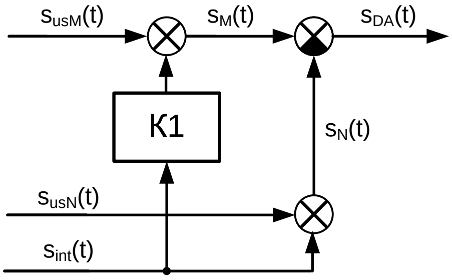


Figure 3. A functional model of a differential amplifier in the presence of an additive mixture of useful and interference components at the input

According to the generalized structural diagram of the receiving path of the phase-metric monitoring system, the next processing step is to compare the phases of the reference and information signals. A device that performs this function is a phase detector, one of the options of which is a circuit based on an analog signal multiplier. The advantage of its using is the ability to obtaining various amplitude characteristics of the detector (cosinusoidal, sinusoidal) depending on the using reference oscillation. Among the disadvantages of using this type of phase detectors, it is necessary to note the need for normalization of input signals, which, however, is quite easily solved by their software implementation by dividing the samples of the input signal by their maximum amplitude value. As a result, the functional diagram of this device can be represented in the form of a multiplier, the inputs of which receive the reference and information signals passing through amplifiers with variable weighted normalizing amplification factors *K2* and *K3* - Figure 4.

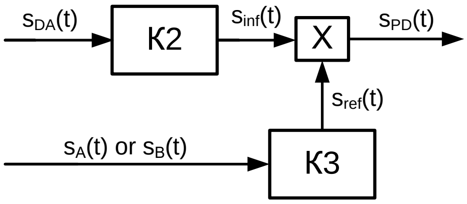


Figure 4. Functional model of a phase detector based on an analog signal multiplier

In general form, the output signal of such a phase detector is defined as

$$s_{PD}(t) = K_{PD} s_{\inf}(t) s_{ref}(t),$$

where K_{PD} is the slope of the linearized characteristic of the phase detector, $s_{\inf}(t) = K_2 s_{DA}(t)$ is the information input signal of the phase detector, $s_{red}(t) = K_3 s_A(t)$ or $s_{ref}(t) = K_3 s_B(t)$ is the reference input signal of the phase detector.

When using a probing oscillation $s_B(t)$ to obtain the reference signal of phase detector, the output signal of the device is determined as

$$s_{PD}(t) = \frac{K_{PD}}{2}\cos(\varphi_{MN} + \Delta\varphi_{MN}(t)) + \frac{K_{PD}}{2}\cos(2wt + \varphi_{MN} + \Delta\varphi_{MN}(t)), \tag{5}$$

and when using probing oscillation $s_A(t)$ it is determined as

$$s_{PD}(t) = -\frac{K_{PD}}{2}\sin(\varphi_{MN} + \Delta\varphi_{MN}(t)) + \frac{K_{PD}}{2}\sin(2wt + \varphi_{MN} + \Delta\varphi_{MN}(t)). \tag{6}$$

The first terms in (5) and (6) are useful components of phase detection (containing trend and dynamic components), and the second are undesirable, to eliminate which it is necessary to use a low-pass filter at the output of the phase detector (information component isolating device in the generalized diagram) with cutoff frequency lying below the spectral component with a frequency $2w$. In the case of using an ideal low-pass filter, its output signal contains only the first term $s_{PD}(t)$ (since such a filter has a unity gain before the cutoff frequency and zero after it)

$$s_{LPF}(t)=\frac{K_{PD}}{2}\cos\left(\varphi_{MN}+\Delta\varphi_{MN}(t)\right) \text{ или } s_{LPF}(t)=-\frac{K_{LPF}}{2}\sin\left(\varphi_{MN}+\Delta\varphi_{MN}(t)\right), \tag{7}$$

and when using the real low-pass filter, its output signal contains both terms, the second of which is attenuated by K_{att} times, where K_{att} is the attenuation coefficient of the real filter at the frequency $2w$

$$s_{LPF}(t)=\frac{K_{PD}}{2}\cos\left(\varphi_{MN}+\Delta\varphi_{MN}(t)\right)+\frac{K_{PD}K_{att}}{2}\cos\left(2wt+\varphi_{MN}+\Delta\varphi_{MN}(t)\right)$$

$$\text{или } s_{LPF}(t)=-\frac{K_{PD}}{2}\sin\left(\varphi_{MN}+\Delta\varphi_{MN}(t)\right)+\frac{K_{PD}K_{att}}{2}\sin\left(2wt+\varphi_{MN}+\Delta\varphi_{MN}(t)\right).$$

We use the assumption about the ideality of the low-pass filter used at the output of the phase detector, for which $K_{att}\to\infty$. In this case, the phase signal $s_p(t)=\varphi_{MN}+\Delta\varphi_{MN}(t)$ in accordance with expression (7) for each of the possible conversion characteristics of the phase detectors is determined as

$$s_p(t)=\arccos\left(\frac{2s_{LPF}(t)}{K_{PD}}\right) \text{ or } s_p(t)=\arcsin\left(-\frac{2s_{LPF}(t)}{K_{PD}}\right). \tag{8}$$

The functional model of this block of the generalized diagram can be depicted as a series connection of three dynamic links, which is shown in Figure 5.

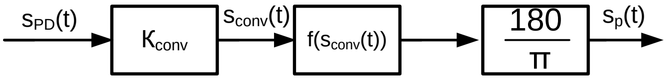


Figure 5. Functional model of a phase signal isolation device

In this scheme, the first block takes into account the multiplication of the output signal of the phase detector by the weight conversion coefficient $K_{conv}=\frac{2}{K_{PD}}$ for the cosinusoidal characteristic of the phase detector or by the coefficient $K_{conv}=-\frac{2}{K_{PD}}$ for the sinusoidal characteristic. The second block of the circuit directly converts the received signal into a phase, and the last block converts it into a degree measure.

Based on the obtained expressions, it can depict the structural and functional models of the receiving path of the phase-metric monitoring system shown in Figures 6 and 7. The following designations are used on the structural diagram: DA - differential amplifier, AVG - amplifier with variable gain, PD - phase detector, LPF - low-pass filter, A - amplifier, CD - conversion device, RG - reference generator.

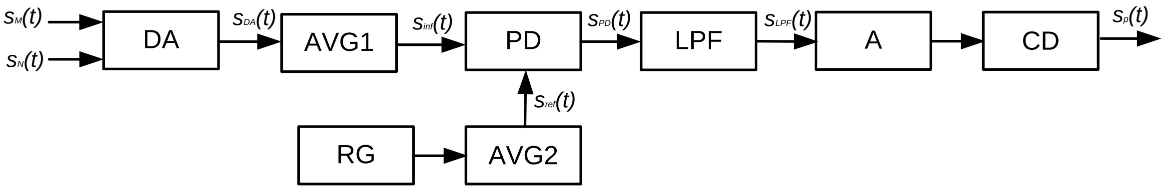


Figure 6. Block diagram of the measuring path of the phase-metric monitoring system

In this scheme, the reference generator RG is a highly stable source of quadrature probing oscillations $s_A(t)$ and $s_B(t)$, the amplifier A is equivalent to the first block of the functional diagram in Figure 5, and the conversion device CD is equivalent to the rest of the blocks at this figure.

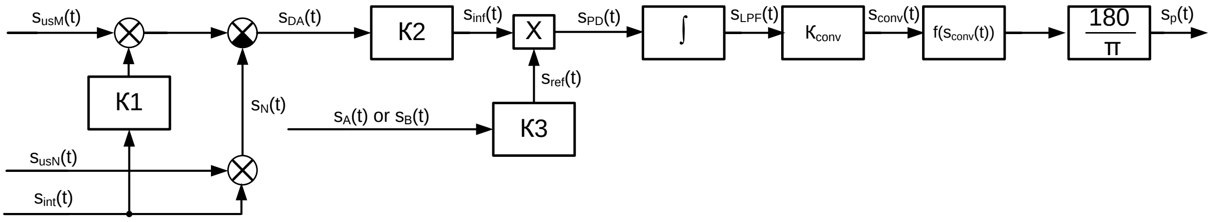


Figure 7. Functional model of the measuring path of the phase-metric monitoring system

4. The results of experimental studies

To approbation the proposed method, experimental studies were conducted on Lake Svyato, Nizhny Novgorod Region, with the aim of geoecological monitoring of geodynamic karst processes [18-21] in the coastal zone of the lake. The layout of the measuring system of local geodynamic control includes a generator module with radiating electrodes and ground, a data recording and pre-processing module with a minimum set of 4 pairs of electric field sensors, a data storage and processing module, as well as registration and measurement modules seismic background, temperature conditions and water level in the lake. Figures 8 and 9 show the scheme and conditions of the layout of the phase-metric measuring system of geodynamic control.

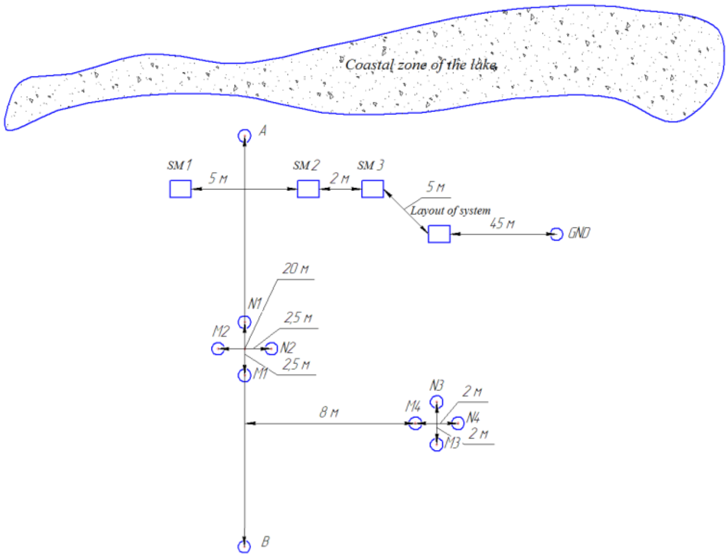


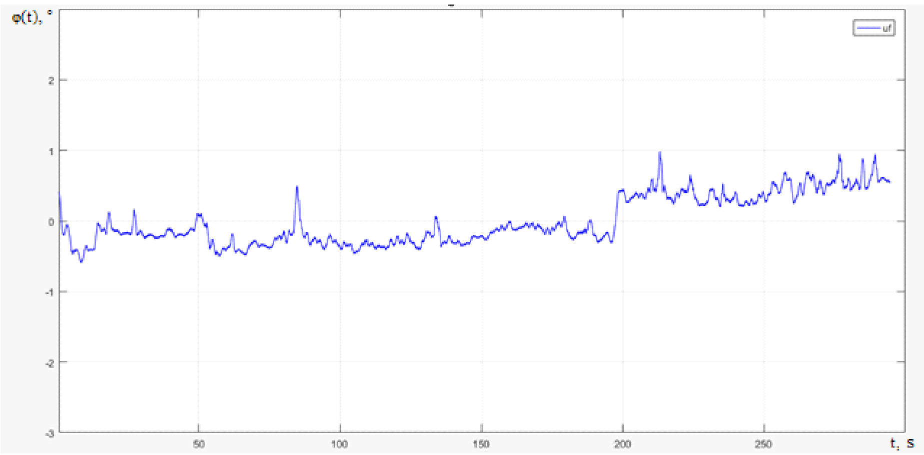
Figure 8. Scheme layout of the phase-metric measuring system of geodynamic control

Figure 9. Photos of scheme layout of the phase-metric measuring system of geodynamic control

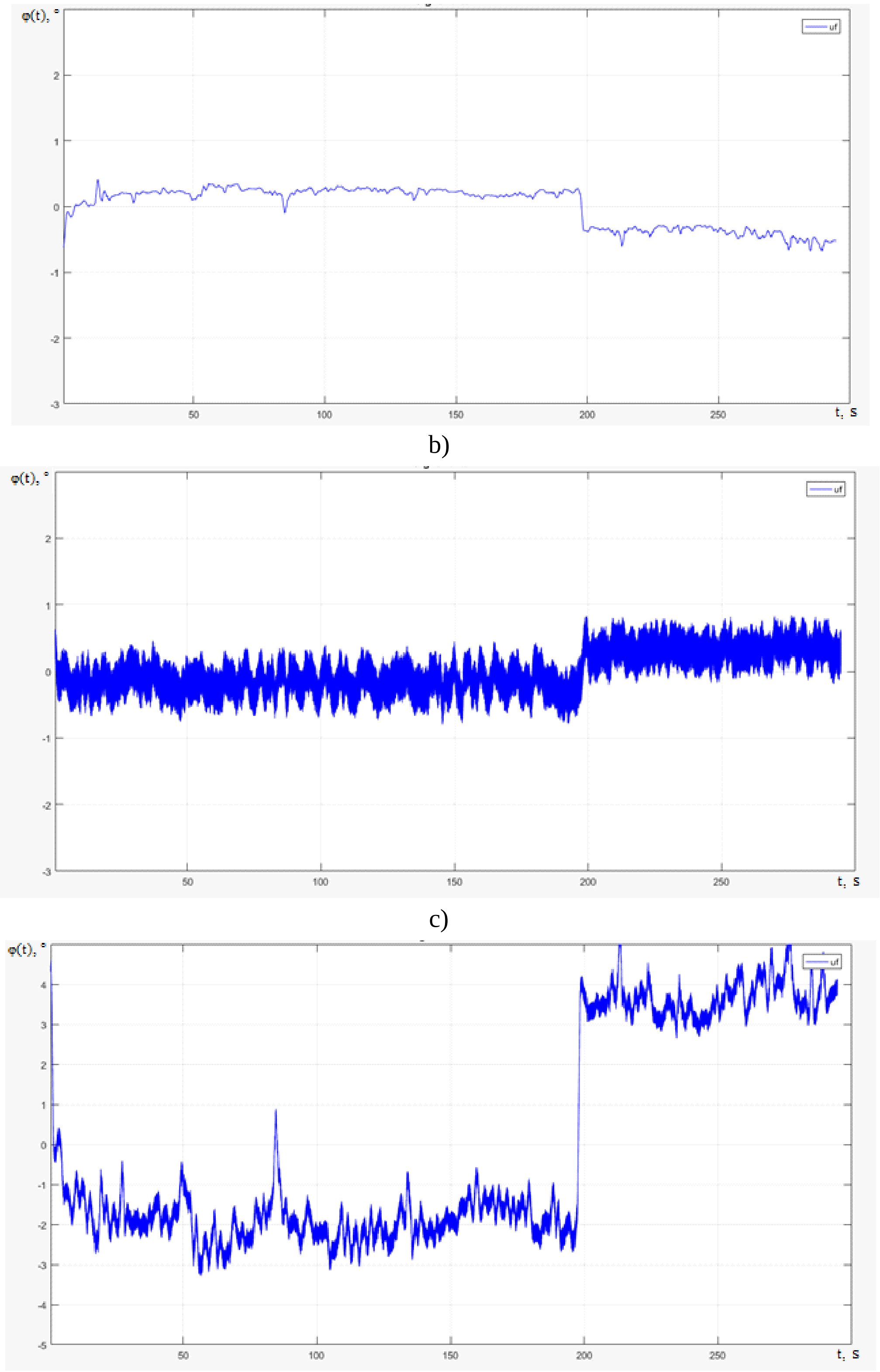
The system deployed on the lake had the following spatial characteristics and parameters:

- The distance between the radiating electrodes AB - 20 m;
- The distance between the receiving electrodes M1N1 is 2.5 m, the location is longitudinal (long line);
- The distance between the receiving electrodes of M2N2 is 2.5 m, the location is longitudinal (long line);
- The distance between the receiving electrodes of M3N3 is 2 m, the location is transverse (near line);
- The distance between the receiving electrodes of M4N4 is 2 m, the location is transverse (near line);
- Frequency of the probing geoelectric signal: 166 Hz, the amplitude from the output of the digital-to-analog converter (DAC) before the power amplifier: 1 V; sampling frequency of the analog-to-digital converter (ADC): 1001 Hz.

In the course of experimental studies, the geodynamic sensitivity of the phase-metric measuring system was assessed by creating an artificial geodynamic impact using a near-surface pit with a depth of 0.5 meters and a diameter of 0.3 meters. Figure 10 shows the results of an experiment to record this geodynamic event at a distance of 60 m from the center of the system for all receiving lines of the layout. The recording time of geoelectric signals in the figure corresponds to 5 minutes, the moment of pit immersion in soil is about 50 seconds from the beginning of data recording, the time of extraction of a pit is about 200 seconds also from the beginning of data recording.



a)



b)

c)

d)

Figure 10. Experimental data of phase signals relative to the longitudinal receiving line M1N1 (a), the transverse receiving line M2N2 (b), the longitudinal receiving line M3N3 (c) and the transverse receiving line M4N4 (d)

From the obtained experimental data, it can be seen that the system based on the phase-metric monitoring method has significant sensitivity to the recording of even extremely small geodynamic events occurring at a considerable distance from the center of the measuring layout. It allows to conclude that the developed method can be effectively used to detect and localize the place of occurrence of a specific geodynamic impact by the analysis the direction of phase changes in the recorded phase signals relative to the stationary state through the use of a network of many pairs of receiving electrodes.

5. Conclusion

The approach presented in this work to the isolation of the phase information component in the signals recorded by geoecological monitoring systems, as well as the proposed structural diagram and the functional model describing it, can be used for practical implementation of the receiving paths of the phase-metric monitoring systems that perform geoecological monitoring of various processes in agricultural development zones of the territories. It should be noted that the proposed method can be implemented in hardware, software or hardware-software.

The effectiveness of the proposed approach is evidenced by the results of its approbation by experimental studies of the layout of the phase-metric measuring system of geodynamic control, carried out near the karst lake to highlight small geodynamic processes in its coastal zone. The results can be used to solve problems of detecting, localizing and evaluating adverse natural and technological processes, forecasting the dynamics of their development, as well as making more effective managerial decisions.

Acknowledgements

This work was prepared as part of the implementation of the state task FZWG -2020-0017 "Development of theoretical foundations for building information and analytical support for telecommunication systems for geo-ecological monitoring of natural resources in agriculture".

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