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Design and Use of Highly Sensitive Induction Sensors for Geodynamic Monitoring

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Abstract: Article is devoted to questions of development and use of active highly sensitive induction sensors in measuring systems of geodynamic monitoring on the basis of geoelectric low-frequency methods. The analysis of options of technical realization of the active induction sensor for geomagnetic researches for the purpose of increase in metrological parameters is carried out. It was found that structurally improve sensor sensitivity can be due to the use of sectioning. At the same time natural resonance frequency of the sensor displaces to the area of the upper frequencies, improving metrological parameters of the magnetometer in general. Assessment of level of a magnetic signal at geodynamic control with use of low-frequency electroprospecting methods is given. It is noted that to achieve the goals inductive sensor must be designed in conjunction with the preamplifier and be connected to a highway filtration through a communication line. Results of the pilot studies directed to measurements magnetic components when using bipolar installation with use of the experimental magnetometer designed taking into account the methods stated in this article are given.

Key words: Geodynamic monitoring, geoelectric control, induction sensors, magnetometry, sensitivity of measurements

INTRODUCTION

Geodynamic environmental changes are daily and widespread and occur with varying degrees of activity depending on the natural and man-caused load on it. Underestimating the impact of natural and anthropogenic phenomena in the environment, occurring at different speeds and intensity can lead to catastrophic consequences (Anisimov *et al*., 2008). Moreover, this is typical not only of sudden disasters such as volcanic eruptions, tsunamis and earthquakes but also to slow exogenous processes such as suffusion processes and karst processes. Respectively, now creation of the highly sensitive equipment of geodynamic control allowing allocating an initial phase of catastrophic changes of the geological environment is urgent.

One approach to solving the problem of early prevention of irreversible changes in the environment is the use of additional measurement information. It can be for example, accompanying magnetic signals in geoelectric methods of geodynamic control (Glangeaurd, 1981). The principle of control and interpretation of magnetic components in the geodynamic monitoring systems which are implemented on the basis of the geoelectric methods of ultra-low frequency range, deserves attention not only theoretical but also from a practical point of view. Method foundations were laid in the 30s when it was proposed to use a magnetic component in order to build isogam with simultaneous interpretation breaks maps (Kuzichkin *et al*., 1999). Later the method was called magnetometric resistivity method (Kuzichkin and Kuligin, 1997). However, this method has been developed and used only for electric survey in prospecting for construction. At the organization of geodynamic monitoring of the requirement to sensitivity and metrological support of the applied methods is several orders higher. It demands improvement of a methodical and algorithmic component of a method.

This study deals with the development and use of of highly sensitive active inductive sensors in measuring geodynamic monitoring systems on the basis low-frequency geoelectric methods and analyzes improve their metrological parameters.

MATERIALS AND METHODS

Measuring the magnetic component in method of resistances: Level of a magnetic signal at geodynamic inspection with use of low-frequency electroprospecting methods can be estimated on the basis of a prime model (Kuzichkin *et al*., 2001). In the assumption of use of

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bipolar electroinstallation with current of intubation of I in the homogeneous isotropic half-space with ρ specific resistance, value of potential in a point of filing of a geoelectric signal will be defined as:

$$\varphi = \frac{I\rho}{2\pi}\left(\frac{1}{r_a} - \frac{1}{r_b}\right),\ r_a = \sqrt{x^2+y^2+(z+\Delta)^2} \qquad (1)$$

$$r_b = \sqrt{x^2+y^2+(z-\Delta)^2}$$

Where:

x, y, z = The coordinates of the registration point location relative to the center of the bipolar electric installation

Δ = Separation feeding electrodes

Taking into account that the vector potential of $\vec{A}$ has the direction of a vector of a current density in the environment $\vec{j} = \vec{\varphi}/\rho$ and according to Maxwell's equations (Tahmassebpour and Otaghvari, 2016) for a projection the parallel base of bipolar installation j_z can write down:

$$-\nabla^2 \vec{A}_z = j_z \qquad (2)$$

Upon transition from Cartesian to a cylindrical frame for the complete current density of j_0 we can write down:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial A_z}{\partial r}\right) = -\frac{j_0}{\left(\sqrt{(1+r^2/a^2)}\right)^3} \qquad (3)$$

where for the magnetic field strength will have the following relationship:

$$H_\phi = \frac{j_0 r}{1 + r^2/a^2 + \sqrt{1+r^2/a^2}},$$
$$H_x = -H_\phi \frac{y}{r},\ H_y = H_\varphi \frac{x}{r} \qquad (4)$$

Respectively, tension of magnetic field along the line of electroinstallation will be equal $H_x = 0$ and in the profile passing through the center and perpendicular to base of electroinstallation $H_y = 0$. On the basis of the received ratios assessment of level of signals of a magnetic field is carried out. For example, for current I = 1A at base electroinstallation a = 100 m the maximal value max $\{H_y\} \approx 1.5$ nT. Obviously, for the registration of such signals is necessary to use highly sensitive magnetometers with specially designed induction sensors (Kuzichkin *et al*., 2001).

Design features of the inductive sensor: Inductive magnetometers which are applied at geodynamic monitoring by geoelectric methods have to provide sensitivity about 0.001 HT and reliable filing of geomagnetic signals with the ultralow-frequency wave band of frequencies with compression of dynamic range. It is one of most complex metrological challenges (Bykov and Kuzichkin, 2014) that is bound to specifics of the frequenciest range of the studied magnetic signals (0.002-5 Hz) and the required sensitivity of the sensor when carrying out monitoring works. In this case the measuring path of magnetometers has to have the stable Amplitude-Frequency Characteristic (AFC) at expansion of a transmission band to 0.002 Hz with the minimum level of characteristic noise and temperature instability (Bykov and Kuzichkin, 2014). In order to achieve these goals inductive sensor is designed in conjunction with a preamplifier (active sensor) and is connected to a filtration path through a communication line. Inductive sensor contains an induction coil of the sensor Lg with a large (hundreds of thousands) number of turns Wg and the coupling coil (calibration) with the smaller (thousands) number of turns W_c (Fig. 1).

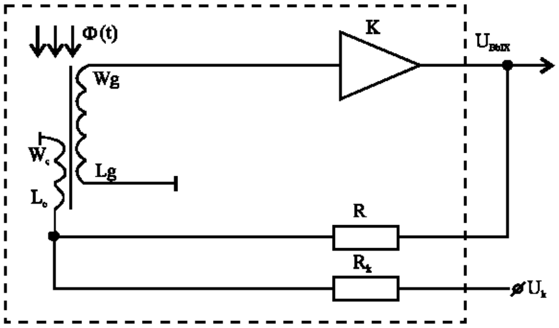

Fig. 1: Scheme of the active inductive sensor

As the core several screwing together rod stock from a permalloy 79NM (Saunin and Telegin, 2014) are used. Given of active resistance and stray capacitances believed that the coils form a transformer with low Q factor. Through resistor R_k is fed the calibration signal U_k for testing of the sensor.

For any spectral component of the magnetic flux Φ(t) with a frequency ω and amplitude Φ_0 signal in the inductive sensor can be written as:

$$e = S_d \frac{d\Phi}{dt} = j\omega S_d \Phi_0 \cos(\omega t) \qquad (5)$$

where, S_d is constructive factor of the coil. The size of the relation e/Φ in Eq. 5 can be considered as a transfer function of the inductive sensor which characterizes operation of derivation over a spectral component of the recorded magnetic field:

$$\kappa_d(p) = j\omega S_d = pS_d \qquad (6)$$

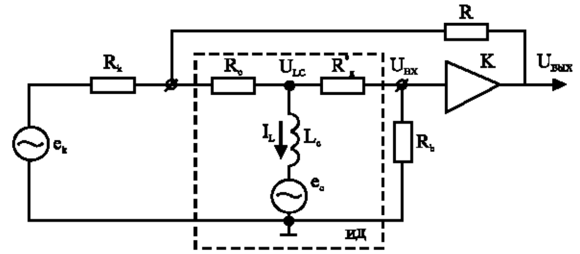

Fig. 2: The dual circuit of the inductive sensor with FB

therefore, the transmission factor of the active sensor of a magnetometer is shows by the work of a transfer function of the inductive sensor K_d and a transmission factor of the signal induced in the coil on a preamplifier exit K_e:

$$K(p) = K_d(p)K_e(p) \tag{7}$$

The transfer function K_e can be obtained from the analysis of the equivalent circuit of an active sensor based on the corresponding equivalent circuit of the transformer. The offered approach is directed first of all to the analysis in the field of ultralow frequencies though the analysis community (at the accounting of physical quantities of conductions) allows to extend it and to area of the top frequencies of the recorded magnetic signals. The dual circuit for the sensor with the Feed-Back (FB) is given in Fig. 2.

For the fissile sensor of a magnetometer with the injected scheme FB the transmission factor can be determined by the formula known from the theory of use of devices with FB (Sharapov and Kuzichkin, 2013):

$$K_2(p) = \frac{K_1(p)}{1+\beta(p)K} = \frac{k_0K}{1+p\tau_g}\,\frac{1+p\tau_c}{1+p\tau_c(1+k_0KR_w/Rn)} \tag{8}$$

Where:

$\tau_c = L_cn^2/R_w$ = The time constant of the circuit FB
$\beta(p)$ = The transfer coefficient FB
$R_w = R_b+R_g$ = The shunt resistance

From Eq. 8 that the introduction of FB is equivalent to adding to the direct transmission K_1 (p) booster unit. In this case, the roots of the characteristic equation are real and independent. Feedback does not affect the value of the time constant of the sensor τ_g and increases the equivalent time constant $\tau_e = \tau_c\ (1+k_0\ K\ R_w/Rn)$ which determines the loop gain of the signal in the active sensor with FB The ratio of permanent sensor time and the feedback loop is independent of the external and internal active resistance of the scheme and is equal:

$$\tau_g/\tau_c = \frac{L_g}{L_cn^2} \tag{9}$$

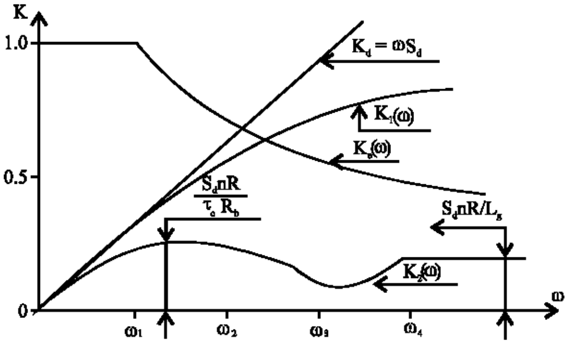

Fig. 3: Amplitude-frequency characteristic of the active inductive sensor

Figure 3 shows the amplitude-frequency characteristics of the active induction magnetometer sensor and its separate units. When developing the input stages of the measuring path of the magnetometer aim is to obtain a large input resistance and thus higher value of the transfer coefficient of the induced signal. Therefore, amplifiers with a serial FB on an entrance are used, however, application of parallel FB allows to expand an amplitude-frequency characteristic of the active sensor to the area of low frequencies.

Ensuring reliability of magnetic measurements: To obtain reliable baseline data at the Geodynamic monitoring requires continuous 24 h data logging. Therefore, one of the main requirements for magnetic measurements is the stability of the transmission characteristics of the measuring path for a long period of work. This problem can not be completely solved even by using highly stable components (Tahmassebpour, 2016). Because of this requires constant monitoring over the parameters of the measuring path recording magnetic signals.

In the active induction sensor (Fig. 1) control is exercised by a compensation method at which on the coil W_c of the sensor the signal compensating the uniform reference magnetic field created by Helmholtz's rings when testing is given. However, it requires suspension of process of registration of magnetic signals and performance of works on testing with big labor input and big costs of time, leading to information losses. Therefore, the solution of a problem of testing of a measuring path without the measurement process termination is very important. Especially, this problem is particularly acute when developing of the modern automated complexes of Geodynamic monitoring (Meirav, 2010). In particular, in

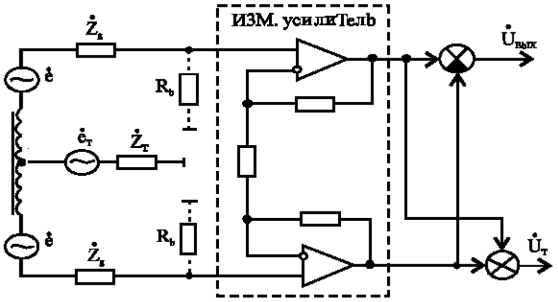

Fig. 4: The equivalent scheme of the active two-section sensor with a source of a test signal

the active two-section sensor for the induction magnetometer it can be reached by introduction of a source of a test signal (Fig. 4).

In the equivalent scheme on Fig. 4, it is designated: $\dot{e}$ the measured signal of tension of the geomagnetic field; $\dot{z}_g$ sensor resistance; $\dot{e}_T$ source of a test signal; $\dot{z}_T$ internal resistance of a source of a test signal.

The signal from an output of the instrument amplifier executed on the standard circuit with gain amount K is connected to the measured strength of a geomagnetic field the following ratio:

$$U(p) = 2k_0K\frac{pS_d}{1+p\tau_g}H(p) \tag{10}$$

In too time, summarizing the strengthened signals from sections of the active two-section sensor it is possible to allocate a signal of reaction to a test signal. The transfer coefficient is determined by a test signal by the following Eq. 11:

$$K_T(p) = \frac{2R_b}{R_g + R_b + pL_g + 2z_T(p)} \tag{11}$$

From Eq. 5 and 7, it is visible that the external measured magnetic field doesn't distort the allocated test signal. In too time, we see that such inclusion of a source of a test signal doesn't influence result of measurement of external magnetic field. It allows to carry out the analysis of parameters of the active induction sensor in a measuring path of the magnetometer along with registration and processing of the registered magnetic signals (Atafar *et al*., 2013).

RESULTS AND DISCUSSION

Results of experimental studies: For the purpose of the organization of carrying out measurement magnetic components when using bipolar installation the experimental magnetometer taking into account the above technique of design of induction sensors.

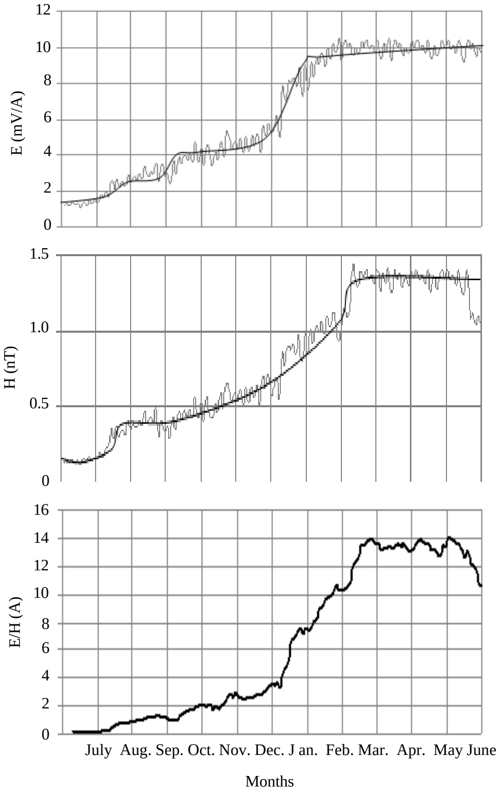

Fig. 5: Interpretation and corrections of data of geoelectric monitoring taking into account dynamics of a magnetic component of the field

During the pilot studies the level of a magnetic signal at geodynamic monitoring with use of low-frequency electroprospecting methods was registered. Accounting and precise inspection of the magnetic field component was carried out in order to correct the data models equipotential multipolar system. As can be seen from the curves shown in Fig. 5, the use of highly sensitive induction sensors can significantly improve the accuracy of geoelectric monitoring.

CONCLUSION

The carried-out analysis of options of technical realization of the fissile inductive sensor for geomagnetic researches gives the chance to draw a conclusion that designly it is possible to increase sensitivity of sensors due to use of their sectioning. At the same time the natural resonant frequency of the sensor is displaced to the area of the top frequencies, improving metrological parameters of a magnetometer in general.

During the experimental studies, it was confirmed that the developed magnetometer as part of geoelectric control system allows not only to increase the sensitivity of the system but also increases the accuracy of predictive estimates from the subsequent data processing and correction of geoelectric section model local areas of the medium.

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