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Effect of a powerful low-frequency signal on an anisotropic medium over hydrocarbon

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Abstract. The article analyses the interaction of a powerful low-frequency signal with an anisotropic medium over hydrocarbon deposits. The behaviour of the real and phase components of the surface impedance of the medium above the deposit in the mode of dual-frequency signals is studied. The analysis of the components of the surface impedance of the medium over hydrocarbons for electromagnetic waves with right and left circular polarizations is carried out depending on the permittivity and frequency of the probing signals. The obtained research results can be used in exploration geophysics to identify the environment above the deposits by the size and nature of the material and phase components of the surface impedance of the surface layer above the hydrocarbons.

1. Introduction

The search for deposits of oil and gas (hydrocarbons) is one of the most important tasks in modern economic conditions. Exploration geophysics widely uses electromagnetic prospecting methods (EMP) to delineate hydrocarbon deposits. The relevance of the tasks considered in this article is determined by the increased requirements for improving the existing EMP methods for detecting hydrocarbon deposits and introducing new methods for their separation and identification. These issues should be resolved promptly, considering their use in a complex geological environment. The use of EMP methods is determined by their high efficiency, environmental cleanliness, and high degree of reliability in comparison with the methods of seismic-geophysical prospecting, gravity and magnetic exploration [1].

The purpose of this work is to increase the information content (sensitivity) and reliability of the detection of hydrocarbon deposits, to determine the boundaries of deposits with high accuracy. At the same time, a great emphasis is placed on improving the productivity of geological exploration. Active research work to solve the assigned tasks is used in practice for the development of EMP methods with the creation of equipment with improved capabilities [2].

The use of EMP methods is based on determining the contrast of rock resistance by changing the characteristics of electromagnetic waves (EM waves) interacting with the medium above the deposits – the amplitudes of the component strengths of the electric and magnetic fields, their phase components, polarization characteristics, etc. The analysis of electro physical and electrochemical processes in the media above the hydrocarbon deposits, their differentiation by electromagnetic properties and the detection of hydrocarbon deposits is carried out on the basis of measuring the resistances at the investigated points of the geological profile using ground electrodes [3].

The interaction of EM waves with the object of research provides a significant set of information and the ability to obtain significantly more data for diagnosing environments with variations in signal parameters in different frequency ranges [4]. Methods for studying complex ionic compounds of a semiconductor nature which present in anisotropic media over hydrocarbons are in widespread use [5].

The methods of electro resonance sounding are based on the optimization of frequency and other parameters of signals, considering the specific characteristics of hydrocarbons deposits [6]. The application of methods based on the analysis and measurement of the surface impedance of the medium above hydrocarbons deposits is determined by taking into account the influence of all the layers below on the upper layer [7]. Diagnostics of media above hydrocarbons can be carried out on the results of studies of permittivity tensors of the medium above hydrocarbon deposits by impact of dual-frequency, modulated and pulsed probing signals on the investigated geological profile [8]. EM wave propagation in the underwater environment is the basis for many methods of hydrocarbon exploration [9]. Obtaining subsalt images is still a challenge in oil and gas exploration. This leads to the complex use of magnetotellurics to improve the integration of seismic and gravimetric data for salt dome imaging, which was actively used in northern Germany [10]. Methods for creating 3D images of the geoenvironment resistivity above the investigated profile based on a vertical-vertical electromagnetic controlled source are an alternative to other EMP methods with a controlled source. It uses a powerful vertical dipole transmitter and arrays of electric field receivers with vertical and horizontal dipole sensors [11]. A universal method for reservoir monitoring and geothermal research can be applied practically to solve problems of electrical exploration [12]. Various modifications of vertical sounding methods are widely used to search for hydrocarbons [13].

The purpose of this work is to select the characteristics of EM waves for a qualitative improvement in the search reliability and identification of hydrocarbon deposits based on the determination of the surface impedance of an anisotropic medium using dual-frequency signals.

2. A method of electrical exploration of hydrocarbons using dual-frequency signals

The search for hydrocarbon deposits is based on the differentiation of the earth's surface by electromagnetic properties. The choice of EM wave characteristics for such tasks is determined by the geoelectric structure and the physicochemical parameters of the investigated surface relief. The solution of the problems of electrical exploration is carried out on the basis of application of various sources of electromagnetic radiation. This is determined by the test specifications, on the basis of which both artificial and natural signal sources can be selected. The search object is determined by the detected electromagnetic anomalies in the given territory.

In this work, to increase search reliability and identification of hydrocarbon deposits, a method based on the sounding of hydrocarbon deposits with a dual-frequency signal is investigated. The kind of this method is:

$$\vec{S}(t) = \vec{S}_1(t) + \vec{S}_2(t) = A_1 \cos \omega_1 t + A_2 \cos \omega_2 t, \tag{1}$$

where A_1, A_2, ω_1, ω_2 – amplitudes and frequencies of two EM waves respectively.

From expression (1) it can be seen that the information content of this method can be significantly higher compared to the harmonic signal, since this effect involves two amplitudes and two frequencies. On their ratio

$$k_E = \frac{A_2}{A_1}, \quad k_\omega = \frac{\omega_1}{\omega_2} \tag{2}$$

the characteristics of the sum signal (1) depend, and this is manifested in the variety of sounding modes. Such effects are especially evident in a significant dynamic range of amplitudes and frequencies of radiation sources. In this article, the problem was limited to the coefficient values $k_E \ll 1$, $k_\omega \ll 1$. To study the properties of the medium above the hydrocarbon deposits, the analysis of the surface impedance of the medium above the hydrocarbon deposits is used according to the formulas

$$\dot{E}_x = -Z_0(\dot{Z}_{11}\dot{H}_x - \dot{Z}_{12}\dot{H}_y),$$

$$\dot{E}_y = -Z_0(\dot{Z}_{21}\dot{H}_x - \dot{Z}_{22}\dot{H}_y),$$

$$\dot{Z}_{11} = \dot{Z}_{22} = -\frac{1}{j2\sqrt{\dot{\varepsilon}_R\dot{\varepsilon}_L}}\left(\dot{\varepsilon}_R - \dot{\varepsilon}_L\right), \tag{3}$$

$$\dot{Z}_{12} = \dot{Z}_{21} = -\frac{1}{j2\sqrt{\dot{\varepsilon}_R\dot{\varepsilon}_L}}\left(\dot{\varepsilon}_R + \dot{\varepsilon}_L\right),$$

where $\dot{E}_x$, $\dot{E}_y$, $\dot{H}_x$, $\dot{H}_y$ – coordinate components of electric and magnetic field strengths;
Z_0 – characteristic resistance of the medium in which the radiation source is located;
$\dot{Z}_{11}$ and $\dot{Z}_{12}$ – components of the surface impedance of the medium;
$\dot{\varepsilon}_R$, $\dot{\varepsilon}_L$ – the total and differential components of the permittivity tensor of the medium over the hydrocarbon deposits, corresponding to the EM waves with right and left circular polarizations, respectively.

Expressions for the permittivity tensor are given in [8]. The method for detecting hydrocarbons is based on the analysis of the surface impedance for different irradiation modes of the studied EM wave profile. This mode corresponds to the effect of a powerful low-frequency (LF) signal on an anisotropic medium. For the application of methods engineering physics for the search for hydrocarbon the use of the equipment operating in the low frequency range is often preferable, since the creation of generators of this range is much simpler compared to high-frequency and super-high frequency units.

3. Research results

Diagnostics of anisotropic media over hydrocarbons is carried out by the difference in the characteristics of the surface impedance of the media in the studied frequency range. The analysis of expressions (3) for the high – frequency component of signal (1) in the range (10^5 – 10^9) Hz at a particle concentration of Ne = Ni = 10^{16} m^{-3} is carried out (a two-particle electron-ion medium is considered). The real and phase components of the surface impedance are studied (figure 1, 2) with variations in the permittivity of the medium.

On the graphs, the values of the third index correspond to the values: 1 – f_2= 10^5 Hz, 2 – f_2= 10^8 Hz, 3 – f_2= 10^9 Hz. It is found that the use of lower sounding frequencies (10^5 Hz) does not affect the value of the surface impedance. This component takes a constant positive value. Increasing the frequency f_2 to a value of 10^8 Hz leads to a change in the nature of the resistance to negative. In this case, the considered component decreases with a variation in the permittivity of the medium in the range from 10 to 30. The application of the frequency of sensing f_2= 10^9 Hz is particularly evident in the change of the component Re $\dot{Z}_{11}$. For values ε_r=1÷3, it decreases to $2.2\cdot10^{-3}$ Ohm.

The segment ε_r= 3-5 is characterized by an increase in the surface impedance, while its zero value is observed at ε_r= 4.2. A further increase in the permittivity of the medium over hydrocarbons is accompanied by a decrease of Re $\dot{Z}_{11}$to zero at ε_r=30.

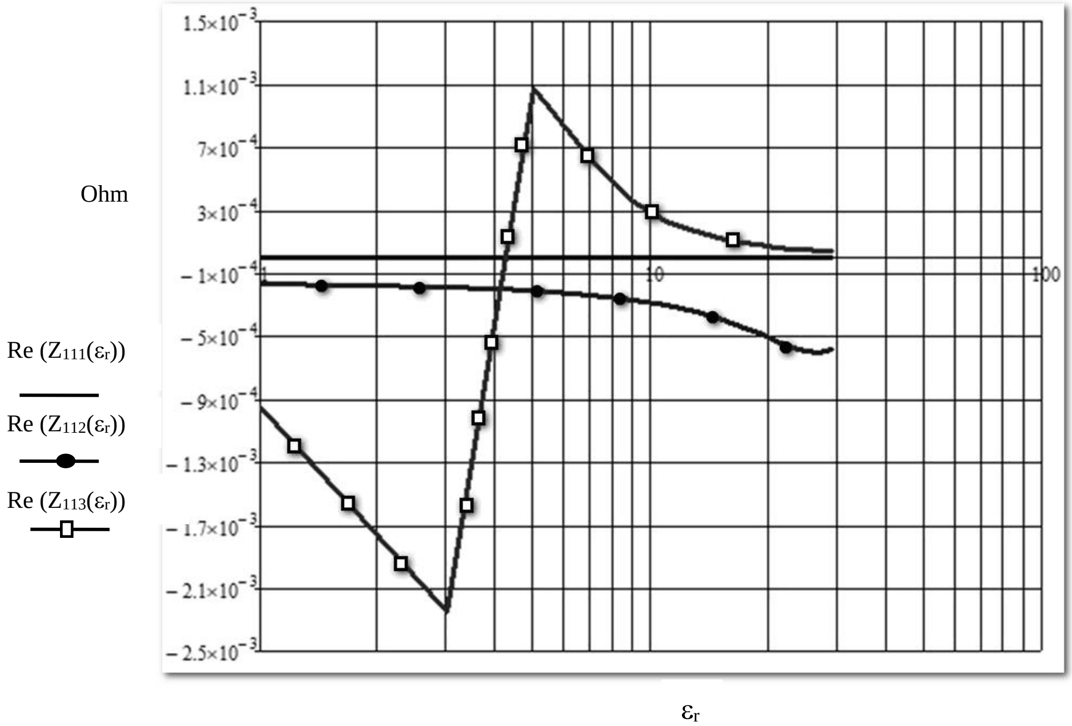

Figure 1. Dependences of the real component $\dot{Z}_{11}$ on the permittivity of the medium.

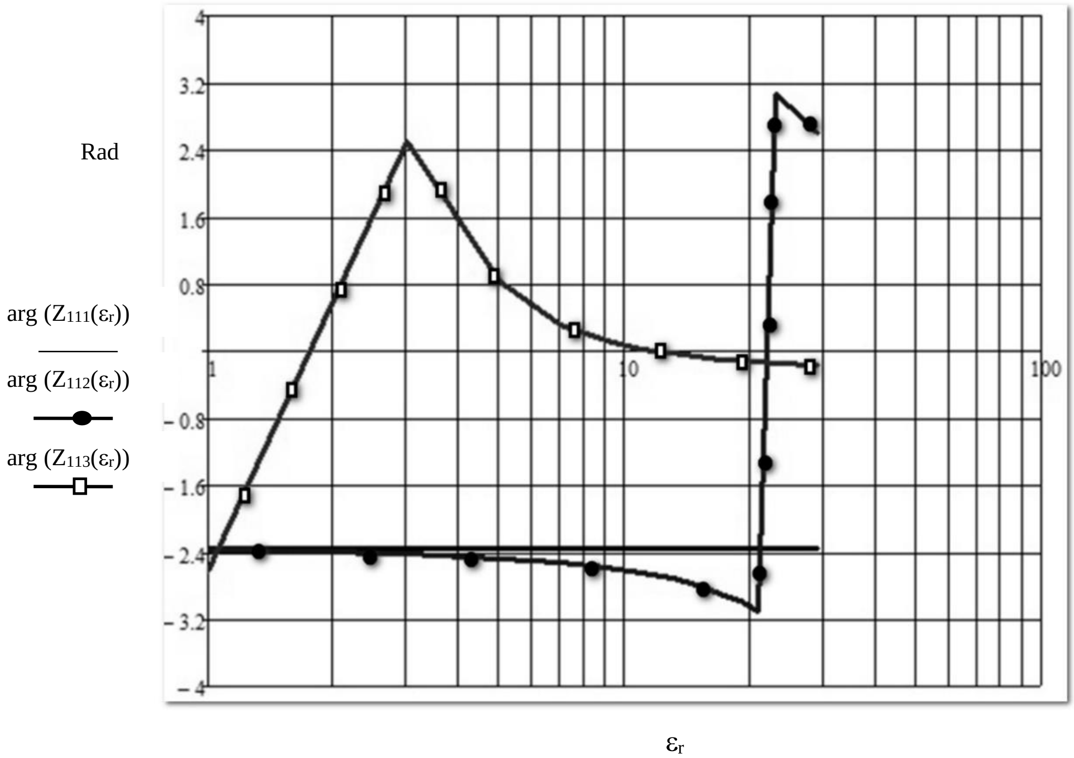

Figure 2. Dependence of the phase component $\dot{Z}_{11}$ on the permittivity of the medium.

The analysis of the phase component showed that the use of low-frequency sounding does not affect its behavior. So at $f_2 = 10^5$ Hz $\arg Z_{11}$ is equal to -2.4 rad. An increase in the frequency with a variation in the permittivity from 3 to 20 leads to a slight decrease in the phase component. The following range of permittivity is of particular interest from the point of view of diagnostics of anisotropic media over hydrocarbon deposits. There is a sharp increase of arg Z_{11} with a transition through zero at $\varepsilon_r = 22$. At the frequency $f_2 = 10^9$ Hz on the interval from 1 to 3, the phase component increases with a transition through zero at $\varepsilon_r = 1.7$. The variation of the permittivity from 3 to 10 is accompanied by a decrease in the considered component to zero, and then the phase of the surface impedance becomes negative when the dielectric constant changes from 10 to 30.

It should be noted that the component $\dot{Z}_{11}$ represents the resistance of the medium for the difference component of the EM waves with right and left circular polarizations. Additional information in such studies is provided by the analysis of the real and phase characteristics of the surface impedance components for EM waves with the sum component for waves with right and left circular polarizations $\dot{Z}_{12}$. The behavior of these characteristics under similar sounding conditions was analyzed (figure 3, 4).

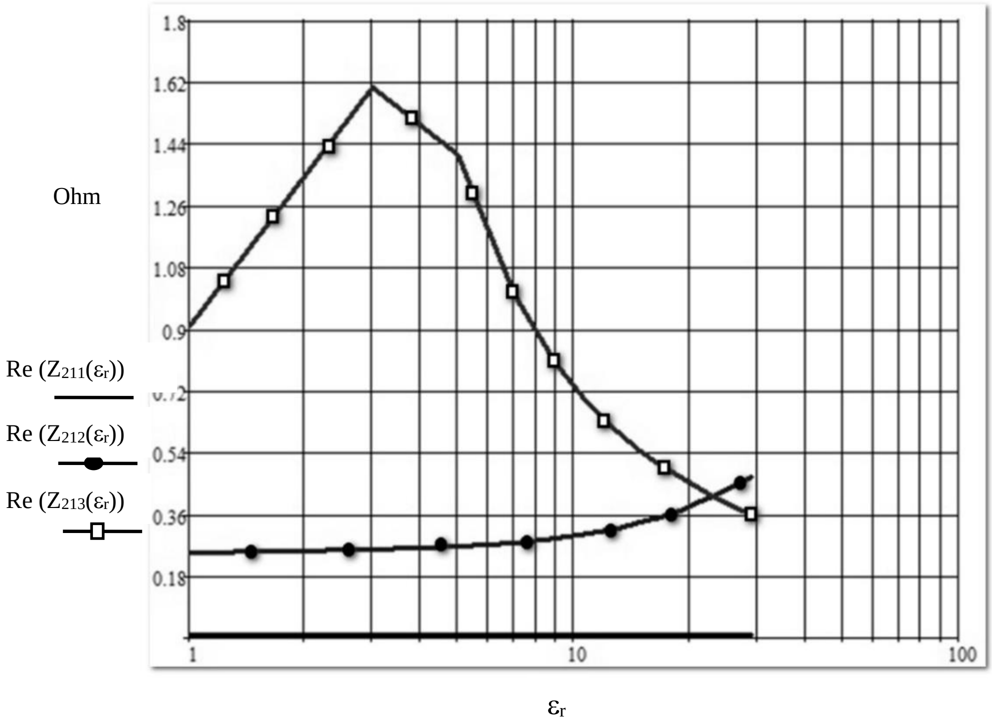

Figure 3. Dependence of the real component $\dot{Z}_{12}$ on the permittivity of the medium.

It is established that the component Re $\dot{Z}_{12}$ = Re $\dot{Z}_{21}$ is uniform in the studied range of permittivity at the sounding frequency $f_2 = 10^5$ Hz, and at its value $f_2 = 10^8$ Hz it increases slightly for higher values of the dielectric permittivity of the medium. The component Re$\dot{Z}_{12}$ has a high-frequency component $f_2 = 10^9$ Hz maximum ($\varepsilon_r = 3$), which is equal to 1.62 Ohm. Further growth of ε_r is accompanied by a decrease in the real component of the surface impedance.

The phase components of the surface impedance $\dot{Z}_{12}$ decrease with increasing permittivity. At the same time, at low frequencies of the radiation sources, the phase practically does not change. For $f_2 = 10^8$ Hz, the phase component decreases at the permittivity interval 10 – 30. The process of diagnosing anisotropic media by phase characteristics can be carried out at a frequency of $f_2 = 10^9$ Hz. At this frequency, the phase sign changes from positive to negative, and the transition through zero corresponds to the permittivity ε_r= 4.4. By moving the transmitter and receiver along the profile under study, additional information is obtained by setting specific distance values.

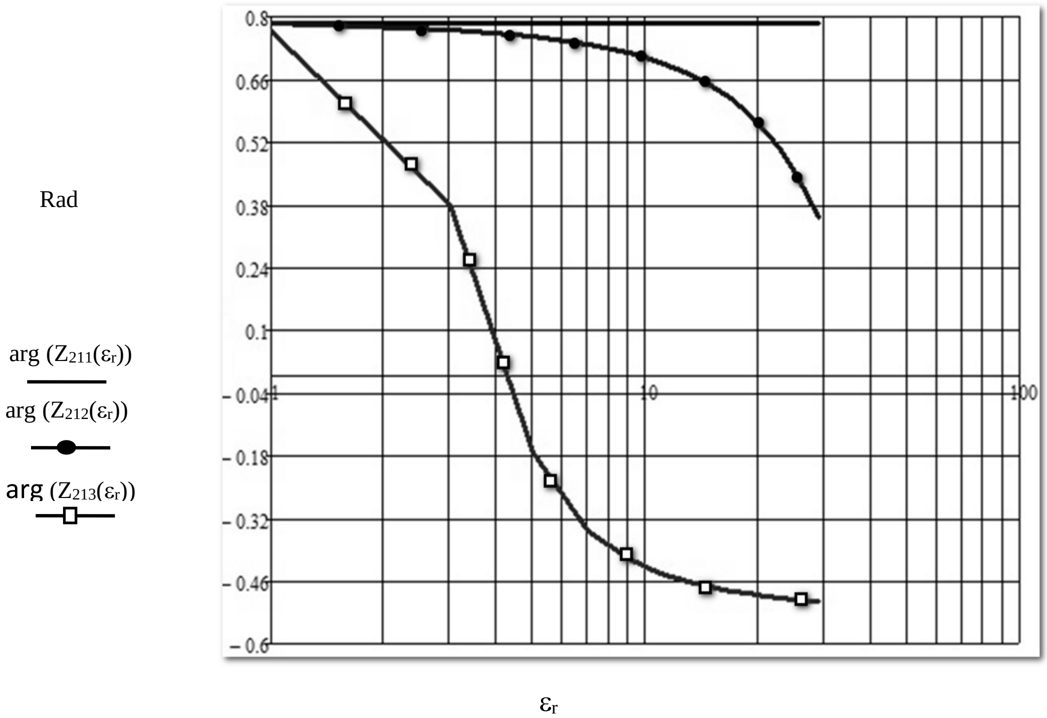

Figure 4. Dependence of the phase component $\dot{Z}_{12}$ on the permittivity of the medium.

The conducted studies expand the database for the diagnostics of media, since numerous components of the properties of reservoir rocks contribute to the value of the surface impedance. The different composition of rocks, depending on their mineralogical properties, granulometric parameters, and skeletal features by structural and textural features, determines the magnitude and nature of the surface impedance.

4. Conclusion

As the result of the analysis it should be noted:

- dual channel definition schema components Re $\dot{Z}_{11}$ and Re $\dot{Z}_{12}$of electromagnetic waves in the modes on the right and left circular polarizations allows to increase the information content of electro prospecting methods;
- the use of frequency f_2= 10^9 Hz leads to a change in the nature of resistance that can be used to identify anisotropic media;
- phase characteristics of the surface impedance indicate changes in the nature of the conductivity when using high-frequency radiation sources.

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