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Determination of phase components of impedance in the environments over hydrocarbon accumulation

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Abstract. The article presents a novel method for hydrocarbon accumulation exploration based on determining the phase components of impedance in environments over hydrocarbons. Experimental studies were conducted at the Rechitsa hydrocarbon field and Osipovichi underground gas storage. The phase characteristics of surface impedance of hydrocarbon accumulation were measured using amplitude-frequency-modulated signals. The results show that determining two components of surface impedance in this mode significantly improves the accuracy of hydrocarbon boundary determination. The developed method can be implemented at frequencies of 0.1-2 GHz, using modulation frequencies of 10-100 MHz, amplitude modulation coefficients of 0.1-1.0, and frequency modulation indices of 20-95. The findings of this research can be applied in electrical exploration for prospecting hydrocarbon accumulation.

1. Introduction

In the current stage of geological surveys, the need for effective methods to locate hydrocarbon accumulations has become increasingly important [1-2]. The authors previously conducted experimental studies measuring the phase of surface impedance over hydrocarbon deposits in the Marmovichi and Geologicheskoye fields of the Gomel region in Belarus using amplitude-frequency modulated electromagnetic waves at carrier frequencies of 0.1-2 GHz, which increased the accuracy of delineating oil and gas deposits [3]. Hydrocarbon boundaries are determined by the reflectance characteristics of the underlying medium above oil-and-gas reservoir using the mode of two-frequency electromagnetic signals with the predominance of powerful low-frequency or powerful high-frequency impact [4].

The method of monotone functions is developed for solving problems of hydrocarbon accumulation search based on binary classification with ordered classes. By the solution method is assumed that the decisive classification rule is related to the ordinal class number of a monotone non-decreasing function of the classification features [5]. Many oil companies use controlled source electromagnetic techniques (CSEM) to determine the distribution of electrical resistivity of the subsurface to unlock the exploration potential here [6]. The article presents the development of industrial use of offshore resource exploration and tectonic studies using data acquisition, modelling technologies [7]. The issues of studying the techniques, methods and technologies of modern field works, as well as the issues of organization and economics of seismic exploration production are widely spread, the requirements to the characteristics of seismic recording equipment (linearity, dynamic and frequency ranges) and the possibilities of their practical implementation are discussed [8]. One example of an exploration technique of hydrocarbon accumulation is to study the response of a geophysical model in shale gas [9]. Onshore hydrocarbon exploration is based on the distinction between resistive and conductive bodies using natural MT fields [10]. 3D resistivity imaging techniques based on vertical-vertical controlled-source electromagnetics provide valuable information about the specific impedance of geological formations [11]. The application of electromagnetic methods has evolved from anomaly detection to mapping, accompanied by the development of improved, faster, and more accurate computer modeling algorithms [12]. Oil field subsidence has been monitored using L-band SAR interferometry [13]. Field surveys of dynamic displacements in tectonic disturbance zones can be used to investigate the properties of the geological profile in an area [14]. Movements of various tectonic structures within the aseismic Bohemian Massif (Czech Republic), particularly along the Sudeten fault zone, have been recorded [15].

Aim of the Research

The primary objective of this study is to develop search techniques for hydrocarbon accumulation using a novel approach based on determining the phase components of impedance in environments over hydrocarbons.

2. Materials and methods

Surface impedance of hydrocarbon accumulation in the amplitude and frequency modulation signals, defined by the expressions [3],

$$\dot{Z}_{11} = \dot{Z}_{22} = -\frac{1}{2j\sqrt{\dot{\varepsilon}_R \dot{\varepsilon}_L}}\left(\sqrt{\dot{\varepsilon}_R} - \sqrt{\dot{\varepsilon}_L}\right),$$

$$\dot{Z}_{12} = \dot{Z}_{21} = \frac{1}{2\sqrt{\dot{\varepsilon}_R \dot{\varepsilon}_L}}\left(\sqrt{\dot{\varepsilon}_R} + \sqrt{\dot{\varepsilon}_L}\right), \quad (1)$$

where $\dot{\varepsilon}_R$ and $\dot{\varepsilon}_L$ – combination components of the permittivity tensor of the medium over hydrocarbon accumulation [3], depends on the amplitude modulation coefficient k_m, frequency modulation index β, carrier frequencies f and modulation F. The application of this type of signal interaction with hydrocarbon accumulation will increase the effectiveness of search and identification methods.

Experimental studies of phase-component measurement (1) of the surface impedance $\varphi_{\dot{Z}11}, \varphi_{\dot{Z}12}$ with linear polarization signal emission were carried out, two measurement channels are used on the receiver-side. In the first channel is measured the phase for the left circular polarization of the amplitude and frequency modulation signals, in the second channel is measured the phase for the right circular polarization of the amplitude-frequency modulation signals.

3. Results and discussion

If only one point of phase measurement (figure 1) is located at the accumulation boundary (reading line 250 for deposit occurrence in Rechitsa), there is a decrease in the phase component $\dot{Z}_{11}$ from a value of 2.5 rad (frequency f = 100 MHz) to a value of – 0.2 rad (frequency f = 700 MHz) and an increase to 0 rad (frequency f = 1000 MHz). On a frequency of f = 1500 MHz there is a decrease in the phase component $\dot{Z}_{11}$ from a value of - 0.3 rad and an increase to 0 rad (frequency f = 2000 MHz). The anomalous values of the phase component $\dot{Z}_{11}$ were used to determine the boundary of hydrocarbon accumulation. If both phase measurement points are located outside the hydrocarbon accumulation, phase differences are observed in two measurement channels with maxima of 0.7 rad (frequency f = 300 MHz) and 0.6 rad (frequency f = 1000 MHz). If both phase measurement points are located over hydrocarbon accumulation, phase differences are observed in two measurement channels with maxima of 0.7 rad (frequency f = 100 MHz) and 0.8 rad (frequency f = 300 MHz).

If only one point of phase measurement (figure 2) is located at the accumulation boundary (reading line 250 for deposit occurrence in Rechitsa), there is a decrease in the phase component $\dot{Z}_{12}$ from a value of 0.3 rad (frequency f = 100 MHz) to a value of 0 rad (frequency f = 2000 MHz), an increase to 0.3 rad (frequency f = 700 MHz) and an increase to 0.2 rad (frequency f = 1500 MHz). The anomalous values of the phase component $\dot{Z}_{12}$ were used to determine the boundary of hydrocarbon accumulation. If both phase measurement points are located outside the hydrocarbon accumulation, phase differences are observed in two measurement channels with maxima of 0.2 rad (frequency f = 300, 500, 700 MHz). If both phase measurement points are located over hydrocarbon accumulation, phase differences are observed in two measurement channels with negative as well as positive skew with minima of - 0,3 rad (frequency f = 300, 500, 700 MHz).

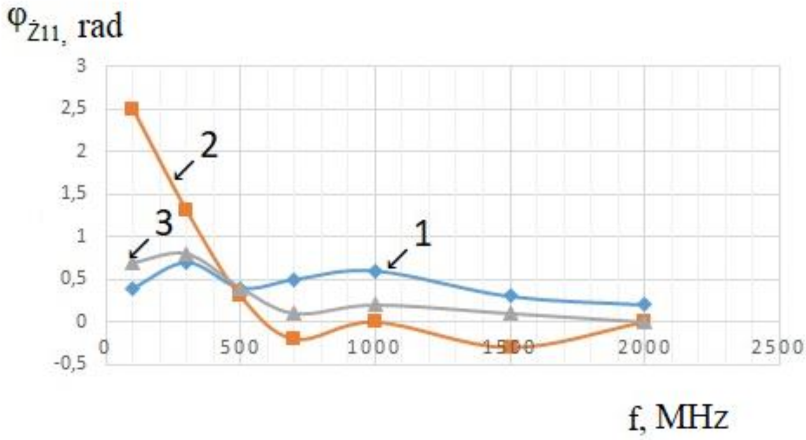

Figure 1. Experimental dependences of the phase component $\dot{Z}_{11}$ for deposit occurrence in Rechitsa: 1 – both points are located outside hydrocarbon accumulation, 2 – one point is located over hydrocarbon accumulation, another one – outside hydrocarbon accumulation, 3 – both points are located over hydrocarbon accumulation.

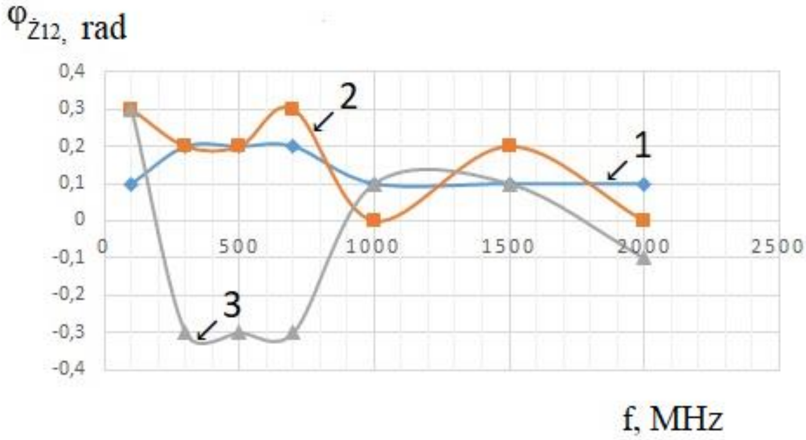

Figure 2. Experimental dependences of the phase component $\dot{Z}_{12}$ for deposit occurrence in Rechitsa: 1 – both points are located outside hydrocarbon accumulation, 2 – one point is located over hydrocarbon accumulation, another one – outside hydrocarbon accumulation, 3 – both points are located over hydrocarbon accumulation.

If only one point of phase measurement (figure 3) is located at the accumulation boundary (reading line 170 for underground gas storage facility in Osipovichi (UGS)), there is a decrease in the phase component $\dot{Z}_{11}$ from a value of 2.3 rad (frequency f = 100 MHz) to a value of 0.1 rad (frequency f = 1000 MHz) and an increase to 0.3 rad (frequency f = 1500 MHz). The anomalous values of the phase component $\dot{Z}_{11}$ were used to determine the boundary of hydrocarbon accumulation. If both phase measurement points are located outside the hydrocarbon accumulation, phase differences are observed in two measurement channels with maxima of 0.5 rad (frequency f = 300 MHz) and 0.5 rad (frequency f = 1000 MHz). If both phase measurement points are located over hydrocarbon accumulation, phase differences are observed in two measurement channels with maxima of 0.5 rad (frequency f = 100 MHz).

If only one point of phase measurement (figure 4) is located at the accumulation boundary (reading line 170 for underground gas storage facility in Osipovichi (UGS)), there is a decrease in the phase component $\dot{Z}_{12}$ from a value of 0.3 rad (frequency f = 100 MHz) to a value of 0.1 rad (frequency f = 700 MHz), an increase to a value of 0.5 rad (frequency f = 300 MHz).

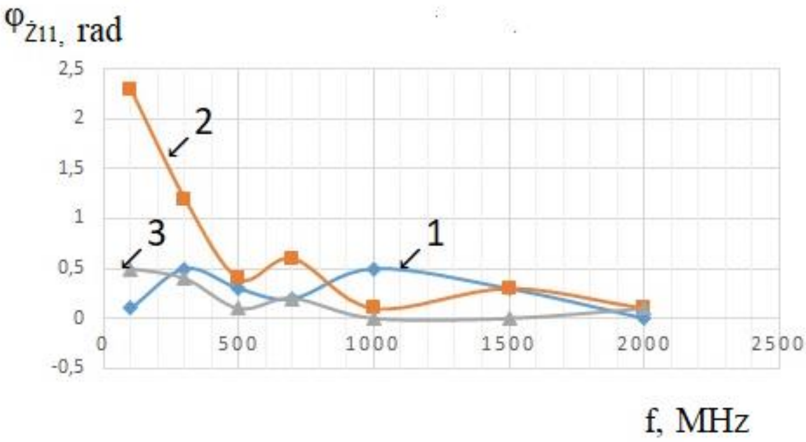

Figure 3. Experimental dependences of the phase component $\dot{Z}_{11}$ for Osipovichi UGS: 1 – both points are located outside hydrocarbon accumulation, 2 – one point is located over hydrocarbon accumulation, another one – outside hydrocarbon accumulation, 3 – both points are located over hydrocarbon accumulation.

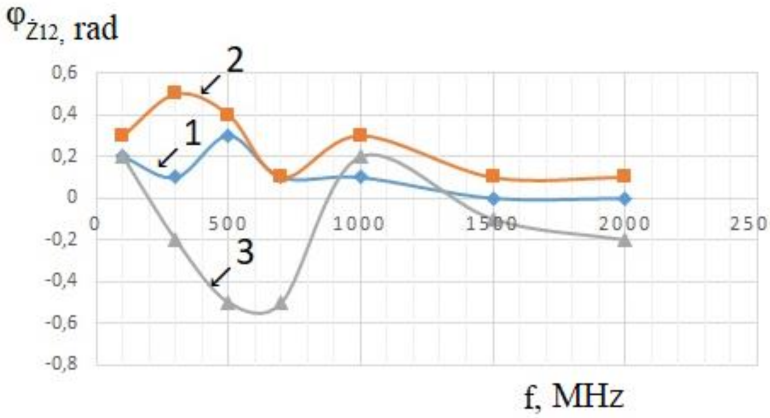

Figure 4. Experimental dependences of the phase component $\dot{Z}_{12}$ for Osipovichi UGS: 1 – both points are located outside hydrocarbon accumulation, 2 – one point is located over hydrocarbon accumulation, another one – outside hydrocarbon accumulation, 3 – both points are located over hydrocarbon accumulation.

At frequency f = 1000 MHz there is an increase in the phase component $\dot{Z}_{12}$ from a value of 0.3 rad and a decrease to 0.1 rad (frequency f = 1500 – 2000 MHz). The anomalous values of the phase component $\dot{Z}_{12}$ were used to determine the boundary of hydrocarbon accumulation. If both phase measurement points are located outside the hydrocarbon accumulation, phase differences are observed in two measurement channels with maxima of 0.3 rad (frequency f = 500 MHz). If both phase measurement points are located over hydrocarbon accumulation, phase differences are observed in two measurement channels with negative as well as positive skew with minima of – 0.5 rad (frequency f = 500, 700 MHz).

Measurements results of phase components of surface impedance are given at modulation frequency F = 10 MHz, frequency modulation index β = 20 and amplitude modulation coefficient k_m = 0.5. The 1st table shows calculation results at amplitude modulation coefficients k_m = 0.1 – 1.0.

Table 1. Calculation results of the phase component of the surface impedance at amplitude modulation index k_m = 0.1 – 1.0.

k_m	Osipovichi UGS		deposit occurrence in Rechitsa	
	$\varphi_{\dot{Z}11}$, rad	$\varphi_{\dot{Z}12}$, rad	$\varphi_{\dot{Z}11}$, rad	$\varphi_{\dot{Z}12}$, rad
0.1	- 0.6 (300MHz)	+0.25 (2000MHz)	- 0.60 (500MHz)	- 0.30 (1500MHz)
1.0	+ 0.20 (1500MHz)	- 0.5 (2000MHz)	+ 0.55 (1500MHz)	- 0.20 (2000MHz)

The 2nd table shows calculation results phase components of surface impedance at modulation frequency F = 50 MHz and amplitude modulation coefficients k_m = 0.1 – 1.0. In this case the values of carrier frequencies are equal to (500 – 1000) MHz.

Table 2. Calculation results at modulation frequency F = 50 MHz, frequency modulation index β = 20 and amplitude modulation coefficients k_m = 0.1 – 1.0.

k_m	Osipovichi UGS		deposit occurrence in Rechitsa	
	$\varphi_{\dot{Z}11}$, rad	$\varphi_{\dot{Z}12}$, rad	$\varphi_{\dot{Z}11}$, rad	$\varphi_{\dot{Z}12}$, rad
0.1	+0.3 (500 MHz)	+0.1 (500 MHz)	+0.5 (700 MHz)	- 0.1 (500 MHz)
1.0	- 0.1 (500 MHz)	+0.1 (500 MHz)	- 0.1 (500 MHz)	- 0.2 (500 MHz)

The 3rd table shows calculation results phase components of surface impedance at modulation frequency F = 100 MHz and amplitude modulation coefficients k_m = 0.1 – 1.0. In this case the values of carrier frequencies are equal to (900 – 1000) MHz.

Table 3. Calculation results at modulation frequency F = 100 MHz, frequency modulation index β = 20 and amplitude modulation coefficients k_m = 0.1 – 1.0.

k_m	Osipovichi UGS		deposit occurrence in Rechitsa	
	$\varphi_{\dot{Z}11}$, rad	$\varphi_{\dot{Z}12}$, rad	$\varphi_{\dot{Z}11}$, rad	$\varphi_{\dot{Z}12}$, rad
0.1	- 0.3 (1500 MHz)	< ±0.1	< ±0.1	+0.2 (1500 MHz)
1.0	- 0.8 (1500 MHz)	- 0.7 (1500 MHz)	- 0.7 (1500 MHz)	- 0.3 (1500 MHz)

The 4th table shows calculation results phase components of surface impedance at modulation frequency F = 100 MHz and amplitude modulation coefficients k_m = 0.1 – 1.0. In this case the values of carrier frequencies are equal to (900 – 1000) MHz.

Table 4. Calculation results at modulation frequency F = 10 MHz, frequency modulation index β = 95 and amplitude modulation coefficients k_m = 0.1 – 1.0.

k_m	Osipovichi UGS		deposit occurrence in Rechitsa	
	$\varphi_{\dot{Z}11}$, rad	$\varphi_{\dot{Z}12}$, rad	$\varphi_{\dot{Z}11}$, rad	$\varphi_{\dot{Z}12}$, rad
0.1	+ 0.9 (1000 MHz)	+ 0.5 (1000 MHz)	+ 0.9 (1000 MHz)	+ 0.3 (1000 MHz)
1.0	+ 0.5 (2000MHz)	+0.6 (1000 MHz)	+ 1.2 (1000 MHz)	+ 0.5 (1000 MHz)

4. Conclusion

The research has led to the development of a novel method for hydrocarbon accumulation exploration. This method can be implemented at carrier frequencies ranging from 0.1 to 2 GHz, using modulation frequencies between 10 and 100 MHz, amplitude modulation coefficients between 0.1 and 1.0, and frequency modulation indices between 20 and 95.

The variation of amplitude modulation coefficients and frequency modulation indices enhances the prospects for discovering hydrocarbon accumulation. Furthermore, determining two components of surface impedance in the mode of amplitude-frequency modulation signals significantly increases the information value of hydrocarbon deposit discovery methods.

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