Principle of relative phase spectrum measurement in SIP

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Summary

Induced polarization (IP) is widely used in oil and gas exploration in the former Soviet Union, Russia, and China. Good results from hydrocarbon exploration were achieved in China recently by applying high-power spectral induced polarization (SIP) with exploration depth exceeding the buried depth of reservoirs. Precision synchronization between the transmitter and receiver is required for the amplitude spectrum and phase spectrum of SIP measurement in the current technology. The synchronization based on the GPS disciplined oven controlled oscillator (OCXO) is the usual method applied in the transmitter and receiver which are used for SIP exploration. The method increases weight and cost of the receiver because the GPS-disciplined OCXO uses the major part of the power consumption of the receiver. Furthermore, this method can not satisfy the measurement requirements of SIP in ocean-bottom conditions because of the lack of GPS signal. We put forward a measurement method of relative phase spectrum (RPS) to resolve the above problem. The IP information of a target is acquired by the amplitude spectrum and RPS of the complex resistivity. The method can decrease power consumption of the receiver by 50% because the RPS measurement does not require synchronization circuit between the receiver and transmitter. The RPS curve shape is similar to that of phase spectrum based on comparing typical parameters of the Cole-Cole model. The RPS owns the same IP information as the phase spectrum. In fact, the RPS formula proposed by here is equal to the phase spectrum formula which is linearly corrected to EM coupling. This was proven through a field experiment. The 3D SIP acquisition can be realized at low cost in the surface, the well, and the ocean-bottom if the phase spectrum measurement is replaced by the RPS measurement. It may expand the application of SIP in oil and gas exploration.

Introduction

The relative phase spectrum (RPS) is closely related to the phase spectrum and the suppression of EM coupling in IP phase measurement. Spies (1983) introduced the progress of geo-electrical exploration in the former Soviet Union after he visited there. Geophysicists of the former Soviet Union put forward a formula that corrects the EM coupling of the IP phase by phase measurements of the 1st and 3rd harmonic of a rectangular wave (Spies, 1983). Hallof (1974) found that the phase shift caused by EM coupling increases approximately linearly with frequency for a uniform or layered earth. Zonge and Wynn (1975) presented a method for removing EM coupling accurately through complex resistivity measurements. Wang *et al.* (1985) put forward a formula to correct PFE measurements with EM coupling effects, and presented a case history with good application results. The RPS formula presented by our research has a similar effect for removing EM coupling as the formula offered by the former Soviet Union geophysicist. It linearly corrects the phase spectrum with the EM coupling effect.

The hydrocarbon search using the IP method experienced a zigzag process in China. The high tide of activity was witnessed in the 1980s in China because of encouragement from the success in the former Soviet Union. People thought that the IP effect in the near surface should be related to hydrocarbon with large buried depth at that time, but this was not always true. A lot of failure cases cooled down people's ardor in China. Sternberg (1991) summarized the condition of hydrocarbon exploration by the IP method in the near surface. The IP anomaly acquired in the near surface is related to hydrocarbon reservoirs only in specified conditions. A series of high power and larger depth SIP explorations for hydrocarbon search was carried out in China since the 1990s. It was found that a hydrocarbon reservoir itself can induce an IP anomaly in the above explorations (He and Jiang, 2005; He *et al*., 2006). He *et al*. (2007) concluded that the anomaly mode and exploration method of SIP from extensive case histories. The research of Davydycheva *et al.* (2006) also indicates that the hydrocarbon reservoir can induce an IP anomaly. The SIP method achieved significant success in China according to the work of He *et al*. (2007).

Two drawbacks exist in the current SIP method compared with the resistivity method. The first is low productivity. The SIP method needs to measure complex resistivity in the frequency range 0.1-100 Hz. It takes about 30 minutes to complete one measurement in a station when the excitation source is a rectangular wave and the data are only acquired on one frequency at a time. The second is that precise synchronization is required between the receiver and transmitter. Only a GPS disciplined oven controlled oscillator (OCXO) synchronization can satisfy the above requirement (Geier *et al*., 1995). But the power consumption of an OCXO is greater than 1 W and uses over 50% of the total power consumption of a typical geophysical data acquisition unit (Panahi *et al*., 2008). Power consumption will increase 10 times at ocean-bottom conditions because a GPS signal is not available. And the power consumption of a double-layer OCXO is typically greater than 10 W. A wide band waveform can be used to replace the rectangular wave to overcome low productivity in SIP method. Duncan *et al*. (1980) tried using a pseudo-random waveform. He (1997) designed several waveforms in which the amplitude spectrum of several harmonics are almost equal in log-scale coordination. Mittet and Schaug-Pettersen (2008) designed several wide-band waveforms for marine CSEM surveys. To overcome the shortcomings of the current SIP method, we acquire the amplitude spectrum on several frequencies simultaneously by applying a wide-band waveform at first. Then we apply the RPS method, which is realized by calculating the RPS based on the wide-band signal to avoid the precision synchronization circuit inside the receiver and transmitter. Our method easily allows for SIP exploration in surface, well, and ocean-bottom conditions with low-power consumption.

Principle of the Relative Phase Spectrum (RPS) Method

Definition of the RPS

The RPS, $\varphi_r(\omega,k)$, of the IP effect is defined as follows:

$$\varphi_r(\omega,k)=\frac{k\varphi(\omega)-\varphi(k\omega)}{k-1}\qquad(\mathrm{k}>1)\qquad(1)$$

In equation (1), $\varphi(\omega)$ is the phase spectrum and k is the frequency ratio, which is a constant. If we calculate the RPS based on the base harmonic and 3rd harmonic of a rectangular wave, k is 3. The value of k is 2, 4, 8, 16, etc., when a wide-band waveform (He, 1997; Mittet and Schaug-Pettersen, 2008) is applied in exploration. The best value of k is 2 or 4 for good productivity.

The Removal of Error in RPS Caused by Synchronization

Let $u(t)$ represent the measured signal by a receiver when the synchronization error does not exist between the receiver and transmitter, where the spectrum of $u(t)$ is $U(j\omega)$. The signal measured by a receiver when synchronization error is τ between the receiver and transmitter is $u(t-\tau)$. The spectrum of $u(t-\tau)$ is $e^{-j\omega\tau}U(j\omega)$ according to the time-shift characteristic of Fourier transform (McGillem and Cooper, 1991). The phase-shift caused by synchronization error is therefore $-\omega\tau$. Set the phase of $U(j\omega)$ to $\varphi(\omega)$, then the phase of $e^{-j\omega\tau}U(j\omega)$ is $\varphi(\omega)-\omega\tau$ accordingly. Phases in frequency ω and $k\omega$ are $\varphi(\omega)-\omega\tau$ and $\varphi(k\omega)-k\omega\tau$, respectively, when the synchronization error between the receiver and transmitter is τ. The RPS $\varphi_r(\omega,k)$ for the above conditions is

$$\begin{aligned}\varphi_r(\omega,k)&=\frac{k[\varphi(\omega)-\omega\tau]-[\varphi(k\omega)-k\omega\tau]}{k-1}\\&=\frac{k\varphi(\omega)-k\omega\tau-\varphi(k\omega)+k\omega\tau}{k\text{-}1}\qquad(2)\\&=\frac{k\varphi(\omega)-\varphi(k\omega)}{k-1}\end{aligned}$$

We can conclude that the RPS $\varphi_r(\omega,k)$ is not affected by the synchronization error between the receiver and transmitter from expression (2). The error in the phase spectrum $\varphi(\omega)$ caused by synchronization error increases proportionally with frequency. For example, if the measurement error is 6.28 mrad for a 1 Hz signal when the synchronization error is 1 ms. The measurement error is 628 mrad for a 100 Hz signal for the same synchronization error. This is why precision synchronization is needed between the receiver and transmitter used in SIP exploration.

Correction of EM Coupling by RPS in the SIP method

The RPS can suppress EM coupling because there is a different relationship between the IP phase and the inductive phase with respect to frequency. The inductive phase changes almost linearly with respect to frequency, but the IP phase changes much slower with respect to frequency. Let $\varphi_{IP}(\omega)$ and $\varphi_{IP}(k\omega)$ be the IP phase of frequency ω and $k\omega$, respectively, $\varphi_{EM}(\omega)$ and $\varphi_{EM}(k\omega)$ are their respective inductive phases. The relative phase between them is as follows:

$$\varphi_r(\omega,k)=\frac{k[\varphi_{IP}(\omega)+\varphi_{EM}(\omega)]-[\varphi_{IP}(k\omega)+\varphi_{EM}(k\omega)]}{k-1}\qquad(3)$$

If the inductive phase is changed linearly with respect to frequency, the following equation exists.

$$\frac{\varphi_{EM}(\omega)}{\varphi_{EM}(k\omega)-\varphi_{EM}(\omega)}=\frac{\omega}{k\omega-\omega}\qquad(4)$$

The simplified form of expression (4) is

$$\varphi_{EM}(k\omega)=k\varphi_{EM}(\omega)\qquad(5)$$

If we consider expressions (3) and (5) together, we have

$$\varphi_r(\omega,k) = \frac{k[\varphi_{IP}(\omega)+\varphi_{EM}(\omega)]-[\varphi_{IP}(k\omega)+k\varphi_{EM}(\omega)]}{k-1} = \frac{k[\varphi_{IP}(\omega)-\varphi_{IP}(k\omega)]}{k-1} \quad (6)$$

Expression (6) shows that the RPS expression defined in equation (1) corrects the EM coupling linearly.

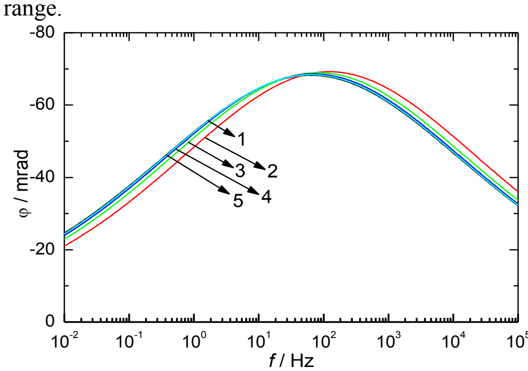
Comparison between Phase Spectrum and RPS

The Cole-Cole model can describe the frequency characteristic of SIP according to measurements acquired on ore sample and outcrop by Pelton *et al*. (1978). The Cole-Cole expression of complex resistivity is following.

$$\rho(j\omega) = \rho_0\left\{1-m\left[1-\frac{1}{1+(j\omega\tau)^c}\right]\right\} \quad (7)$$

where ρ_0 is the resistivity at zero frequency, and m, τ, and c are the chargeability, time constant, and frequency dependence, respectively. The phase spectrum and RPS can be calculated based on expressions (7) and (1).

We chose typical parameters for a Cole-Cole model to compute the phase spectrum and RPS (m = 0.5, τ = 0.01s, $c=0.25$ and $k=2$, 8, 32, 128). The frequency range is from 0.01 Hz to 10,000 Hz. Four hundred points are sampled at the log-scale coordinate in the above frequency range.



1—$\varphi(\omega)$; 2—$\varphi_r(\omega,2)$; 3—$\varphi_r(\omega,8)$; 4—$\varphi_r(\omega,32)$; 5—$\varphi_r(\omega,128)$

Figure 1: RPS and phase spectrum curve (m = 0.5, τ = 0.01s, c=0.25)

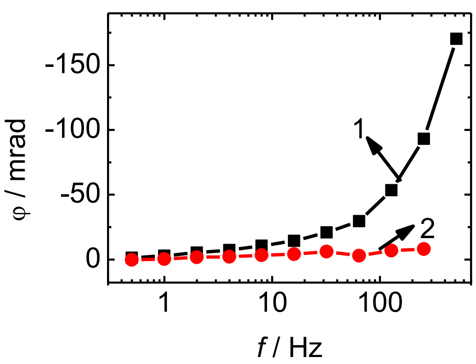
Figure 1 indicates that the curve shapes of the RPS and phase spectrum are similar, and the difference between RPS and the phase spectrum is reciprocally proportional to the frequency ratio, *k*.

Data Acquisition Method for Relative Phase Spectrum

The transmitter and receiver should possess real-time clocks for successful RPS measurement, and the errors of each clock should be less than 60 s for the entire data acquisition process. This requirement is very low compared with the requirement for phase measurement. The receiver can work continuously for a month in the submarine by using a usual crystal oscillator because the time error inside a receiver will be less than 60 s in a month. The transmitters can continuously record the current waveform at the same sampling frequency as the receiver and store the data every second. The receiver simultaneously records the waveform of the potential difference each second at the same time. The sampling frequency inside the transmitter and receiver should be the same to ensure correct processing, and be greater than 10 times the signal frequency. The change of transmitting current caused by the change of grounding conditions within 60 s will not produce significant errors in the measurement of RPS. After completing the data acquisition, the data processing program reads the data different potential signal and corresponding current signal according to the signal sampling time, and then calculates the transfer function of the potential difference signal and current signal by carrying out a Fourier transformation. By using formula (1), the relative phase spectrum can be calculated from the phase spectrum of the transfer function. A large synchronization error between the transmitter and receiver may exist; therefore, the calculated results of the phase spectrum may also have a large error. However, there is no impact on the accuracy of the RPS measurement, because RPS measurement is not effected by synchronization error between the receiver and transmitter.

Test for RPS and Phase Spectrum Measurement

The test was conducted on the region which did not have an obvious IP anomaly in the south of China. The dipole-dipole array was used in the test. The corresponding parameters were *a*=*AB*=*MN*=20 m and *n*=1 for dipole-dipole array. The supply current *I* was 88 mA. The transmitting waveform is the multi-frequency waveform with frequency range from 0.5 to 512 Hz, which was designed by He (1997). In order to compare the difference between the phase spectrum and RPS, we measured them at the same time.



1—phase spectrum $\varphi(\omega)$; 2— RPS $\varphi_r(\omega,2)$

Figure 2: Phase spectrum and RPS curves

Figure 2 shows that the absolute value of the phase spectrum resulting from the inductive coupling changes almost linearly with the logarithmic frequency coordinate. The maximum caused by inductive coupling is less than 8 mrad for the RPS measurement. It is clear that the inductive coupling has been linearly corrected by the RPS measurement.

Conclusions

RPS measurement avoids the error in phase spectrum measurement caused by the synchronization error between the transmitter and receiver. A special hardware synchronization circuit is not required in the transmitter and receiver for RPS measurement. The receiver power consumption can be reduced in the above condition. Our method removes the restriction of GPS signal or other similar restrictions for SIP exploration. The SIP 3D data acquisition can be realized on land, in wells, and in submarines without a GPS signal if our method is adopted.

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EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2009 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

Davydycheva, S., N. Rykhlinski, and P. Legeido, 2006, Electrical-prospecting method for hydrocarbon search using the induced-polarization effect: Geophysics, **71**, no. 4, G179–G189.

Duncan, P. M., A. Hwang, R. N. Edwards, R. C. Bailey, and G. D. Garland, 1980, The development and applications of a wide band electromagnetic sounding system using a pseudo-noise source: Geophysics, **45**, 1276–1296.

Geier, G. J., T. M. King, H. L. Kennedy, R. D. Thomas, and B. R. McNamara, 1995, Prediction of the time accuracy and integrity of GPS timing: Proceedings of 49th Annual IEEE International Frequency Control Symposium, 266–274.

Hallof, P. G., 1974, The IP phase measurement and inductive coupling: Geophysics, **39**, 650–665.

He, J., 1997, Frequency domain electrical methods employing special waveform field sources: 67th Annual International Meeting, SEG, Expanded Abstracts, 338–341.

He, Z., and W. Jiang, 2005, Hydrocarbon detection with high-power spectral induced polarization, two cases: 75th Annual International Meeting, SEG, Expanded Abstracts, 599–601.

He, Z., W. Jiang, and P. Liu, 2006, Two case studies from China of hydrocarbon detection with SIP: The Leading Edge, **25**, 1401–1402.

He, Z., H. Liu, and B. Tang, 2007, Geoelectrical anomaly patterns of reservoir and geoelectrical methods for direct reservoir detection: 77th Annual International Meeting, SEG, Expanded Abstracts, 698–702.

McGillem, C. D., and G. R. Cooper, 1991, Continuous and discrete signal and system analysis: W. B. Saunders Co.

Mittet, R., and T. Schaug-Pettersen, 2008, Shaping optimal transmitter waveforms for marine CSEM surveys: Geophysics, **73**, no. 3, F97–F104.

Panahi, S. S., S. Ventosa, J. Cadena, A. Manuel-Lazaro, A. Bermudez, V. Sallares, and J. Piera, 2008, A low-power datalogger based on compactflash memory for ocean bottom seismometers: IEEE Transactions on Instrumentation and Measurement, **57**, 2297–2303.

Pelton, W. H., S. H. Ward, P. G. Hallof, W. R. Sill, and P. H. Nelson, 1978, Mineral discrimination and removal of induction and removal of inductive coupling with multifrequency IP: Geophysics, **43**, 588–609.

Spies, B. R., 1983, Recent developments in the use of surface electrical methods for oil and gas exploration in the Soviet Union: Geophysics, **48**, 1102–1112.

Sternberg, B. K., 1991, A review of some experience with the induced-polarization/resistivity method for hydrocarbon surveys: Successes and limitations: Geophysics, **56**, 1522–1532.

Wang, J., K. Zhan, L. Shien, and L. Yan, 1985, Fundamental characteristics of an approximate correction method for electromagnetic coupling in frequency-domain induced polarization: Geophysics, **50**, 235–241.

Zonge, K. L., and J. C. Wynn, 1975, Recent advances and applications in complex resistivity measurements: Geophysics, **40**, 851–864.