NONLINEAR EFFECT OF THE DUAL-FREQUENCY IP SPECTRUM①

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ABSTRACT Experiments were carried out on more than fourty various mineral specimen with the dual-frequency IP instruments in a closed condition and a 3-D water tank to study the nonlinear effect of the dual-frequency IP spectrum. The comparison of experimental and theoretical analysis results showed that the sawtooth feature will be appeared on the dual-frequency IP spectral curves when the induced current density is increased to a certain value, and the feature is different for different minerals. Based on this feature, it is possible to develop a new geopgysical method to evaluate the IP anomalies using the dual-frequency IP method.

Key words nonlinear effect spectral curves sawtooth feature dual-frequency IP method

1 INTRODUCTION

Many scholars have done researches on IP nonlinear effect[1-5], among others Sumner J S observed that the IP effect of rocks/minerals changes obviously with the variation of the induced current density[6]; resistivity and IP effect decrease clearly and the IP spectral curves turns to be smooth when the induced current was greater than a certain values[7].

Experiments also showed that the cathodic polarization curves are different from the anodic polarization curves[8]. In general, the anodic polarization for the metallic sulfides is stronger than its cathodic polarization, i. e. it is of "the anodic polarization dominant"; while the carbonaceous minerals such as graphite show opposite property, i. e, it is of "the cathodic polarization dominant". So it is possible to distinguish the IP anomalies of different minerals using IP nonlinear effect.

In this paper, the nonlinear effect of IP spectrum when the induced current density is relatively small is studied using the dual-frequency IP method. Experiment results showed that, with the increase of the induced current density, not only the mineral's resistivity decreases and the IP effect fades, but also a sawtooth feature appears on amplitude and phase (or real and imaginary component) spectral curves. The sawtooth feature is a special phenomenon of IP nonlinear effect on the dual-frequency IP spectral curves, which can be used to evaluate the IP anomalies.

2 NONLINEAR EFFECT OF DUAL FREQUENCY IP SPECTRUM

2.1 *Theoretical Analysis*

A new equivalent circuit to simulate the mineral-electrolyte system has been described in Ref. [1], where the overvoltage induced by arbitrary current was also calculated. It was shown that the nonlinear IP effect would be different when induced with different current waveform. Here, we shall discuss the nonlinear IP effect when the circuit is induced with the dual-frequency current based on the results in Ref. [1].

The key technique of the dual-frequency IP method is that, the transmitter provides a dual-frequency current composed of a basic

① Supported by the National Natural Science Foundation of China; Received Nov. 11, 1994

frequency and its 13th harmonic frequency to the earth at the same time, and the receiver records the IP response of the earth to the dual-frequency simultaneously. The main component of the dual-frequency current may be written as[2]:

$$I(t) = I\cos wt - \frac{12}{13} I\cos(13wt) \qquad (1)$$

After expanding the equation (1) we get four items which are $k = -13, -1, 1, 13$ in power series and $I_k = -12I/13, I, I, -12I/13$ in amplitude respectively. Put them into the overvoltage expression, we get further the overvoltage response of the equivalent circuit to the dual-frequency current in time domain. Thus, the IP response in frequency domain can be obtained by Fourier transform. There are not only the items in the response $V(w)$ containing the two frequencies (i. e, $w' = w, 13w$), but also the items containing the combined frequencies (i. e, $w' = 2w, 3w \cdots$). Here, we will not discuss the combined frequency components further more since it was not recorded in the following experiments.

As for the items containing the two frequencies, the complex impedance definition was also used to describe the IP response. Ignoring the high order minimum, the complex impedance can be expressed approximatey as follows:

$$Z(w') = Z'(0)\left[1 - m'\left(1 - \frac{1}{1 + (iw'\tau')^{c}}\right)\right] \qquad (2)$$

where $Z'(0) = R_b + R'_c(w')$

$m' = R'_c/[R_b + R_c(w')]$

$\tau' = \chi[R'_c(w')]^{\frac{1}{c}}$

and $R'_c(w) = R_c/(1 + 2.0286bj^2)$

$R'_c(13w) = R_c/(1 + 2.1391bj^2)$

In the above expressions, R_b is the resistance of electrolyte, R_c the linear resistance of nonlinear Faradaic path, b the nonlinear IP effect of the Faradaic path, m' the chargeability, τ' the time-constant, χ the capacitive resistance of the double layer and j the induced current density.

Note that, in the above expressions, the impedance is different for the two frequencies in the dual-frequency current, and the resistance of the Faradaic path to the 13th harmonic frequency is little smaller than that to the basic frequency. Thus, for the same frequency, the IP nonlinear effect is different when it is transmitted as the basic frequency and as the 13th harmonic frequency. The nonlinear effect for the 13th harmonic frequency is stronger than that for the basic frequency. Therefore, the sawtooth feature appears at the neighbouring frequency point on the dual-frequency IP spectral curves.

Figs. 1 and 2 show the theoretical spectral curves calculated for metallic sulfides and car-

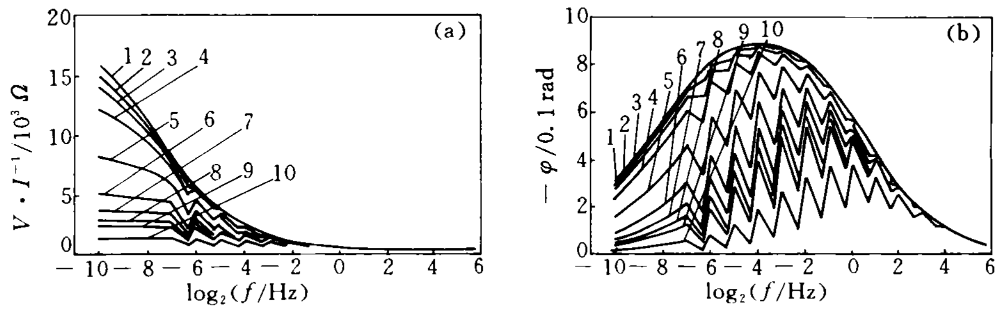

Fig. 1 Theoretical dual-frequency IP spectral curves for metallic sulfides

(a)—amplitude; (b)—phase

$Z(0) = 20\,000\,\Omega$, $m = 0.985$, $\tau = 50\,s$, $c = 0.7$, $b = 0.015\,cm^4/\mu A^2$

The current density for curves 1~10 is

0, 1, 2, 4, 10, 20, 30, 40, 50, 100 μA^2, respectively

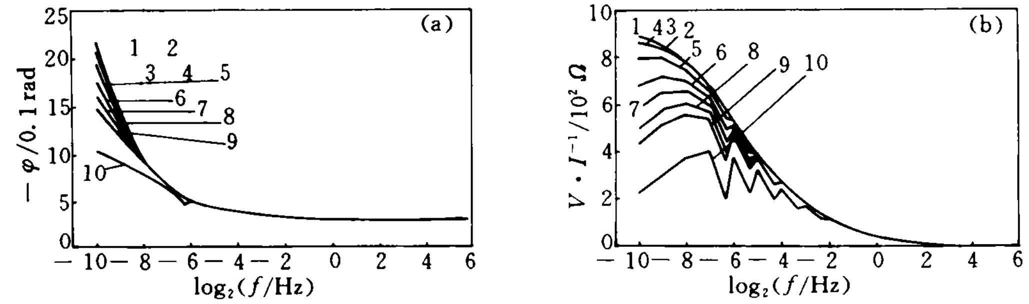

Fig. 2 Theoretical dual-frequency IP spectral curves for carbonaceous minerals

(a)—amplitude; (b)—phase

$Z(0)=20\,000\,\Omega$, $m=0.985$, $\tau=2\,000$ s, $c=0.7$, $b=0.015\,\text{cm}^4/\mu\text{A}^2$

The current density for curves 1~10 is 0, 1, 2, 4, 10, 20, 30, 40, 50, 100 μA^2, respectively

bonaceous minerals induced by the dual-frequency current, respectively. It is clear that the sawtooth feature appears on the dual-frequency IP spectral curves with the increase of the induced current density, and this sawtooth feature is different for different minerals. The current density necessary for the appearance of this nonlinear effect is much smaller for the metallic sulfides than that for the carbonaceous minerals.

2.2 *Experimental results*

Fig. 3 shows the experiment apparatus, which satisfied the closed condition. In the center part of a 8 cm × 8 cm × 8 cm organic glass tank, there is a cubic compact specimen covered with rubber lining at each side excepting the right and left sides for seperating the electrolyte. The electrolyte in the tank is Na_2SO_4 of 0.005 mol, the potential electrodes M and N are put into the electrolyte at the right and left sides respectively of the specimen through a salt bridge for avoiding the pollution of Na_2SO_4. The salt bridge is made of agar and KCl, of which one end has a small calibre of 2 mm in thickness and is about 3 mm apart from the specimen. The other end of the bridge is a U shape glass tube, connecting to a beaker. Inside the beaker, there is saturated electrolyte (KCl), which is connected to inlet of a receiver through a 232 saturation calomel electrode above the beaker. the current electrodes are a series of connected carbon sticks (three for each) set at both ends of the tank. A standard resistance is connected in series with the circuit for verification.

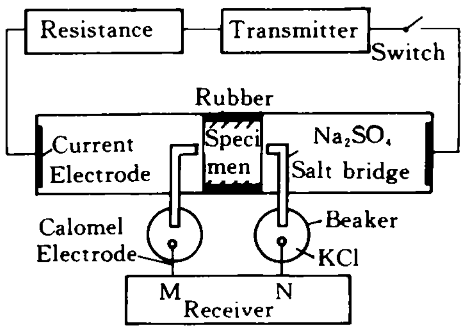

Fig. 3 The apparatus used in experiments

The transmitter and receiver used in the experiments are the dual-frequency spectral IP transmitter and receiver with multi-parameters. Each time, the transmitter transmits the dual-frequency current into the experimental tank. The receiver records the amplitude/phase or the real/imaginary components of the overvoltage response of the specimen to the two frequencies simultaneously. the transmitter can provide 8 pairs of frequencies to compose a spectral measurement from 0.029 Hz to 32 Hz, those pairs of frequencies are: 32 Hz and 32/13 Hz, 16 Hz and 16/13 Hz, 8 Hz and 8/13 Hz, 4 Hz and 4/13 Hz, 2 Hz and 2/13 Hz, 1 Hz and 1/13 Hz, 0.5 Hz and 0.5/13 Hz, 0.25 Hz and 0.25/13 Hz, respectively.

There are more than 40 specimens, including pyrite, chalcopyrite, galenite, blenite, blende, chalcocit, psilomelane and other metallic sulfides; also some oxide minerals as magnetite, hematite; some carbonaceous minerals as graphite, anthracite coal and carbonaceous phyllite, etc. Before experiment all those specimens should be immersed in Na_2SO_4 electrolyte for more than 24 hours.

Experiment results showed that, for most minerals, the sawtooth feature will appear on the dual-frequency spectral curves when the induced current density is increased to a certain value. Furthermore, the sawtooth feature is different for different types of minerals. Figs. 4 ~ 8 show the experimental results of three typical kinds of minerals. (a) For the metallic sulfides and magnetite (Figs. 4~6), the induced current density necessary for the appearance of the sawtooth feature on the dual-frequency IP spectral curves is fairly small. Generally, the sawtooth feature appears when the induced current density is about 1 $\mu A/cm^2$, especially on the phase spectral curves, of which the sawtooth appears even at more higher frequencies. (b) For carbonaceous minerals such as graphite (Fig. 7), the induced current density necessary for the appearance of the sawtooth feature is about 50 $\mu A/cm^2$, which is much greater than that for the sulfides and magnetite. At higher frequencies, the sawtooth feature will not appear on the dual-frequency spectral curves even when the induced current density is very large. (c) Fig. 8 shows the dual-frequency IP spectral curves for hematite, which is different from that showed in Figs. 4~7. Firstly, with the increase of the induced current density, the phase will not change obviously, while the amplitude increases. Secondly, the upper point of the sawtooth on the spectral curves is at the higher frequency point of the dual-frequency current, and the lower point is at its lower frequency point. These two features are just opposite to that of the spectral curves for sulfides and carbonaceous minerals. Because hematite is a high resistance oxide mineral, the induced current density can not be increased to a value large enough for the appearance of the sawtooth feature. Besides, hematite (except some varieties) is not conductor, so the analysis relating to sulfides and carbonaceous minerals is not suitable for hematite.

2.3 *Experiment in 3-D Water Tank*

In order to model the field condition, and to verify the theoretical analysis, some experiments were carried out in a 3-D water tank with gradient array. The tank's size was 3.0 m

2.3.1 Experiment result

A dual - frequency current of 2 Hz and 2 6

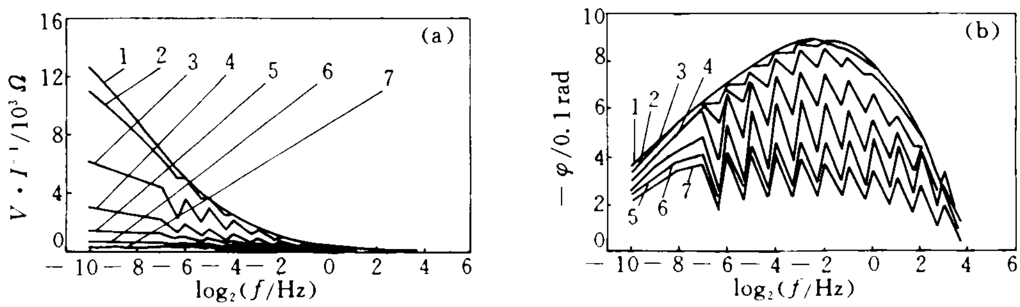

Fig. 4 The dual-frequency IP spectral curves for pyrite (23.4 cm^2 × 4.2 cm)
(a)—amplitude; (b)—phase
The current density in experiment for
curves 1~7 is 0.16, 0.83, 3.16, 12.16, 38.30, 87.50, 127.40 $\mu A/cm^2$, respectively

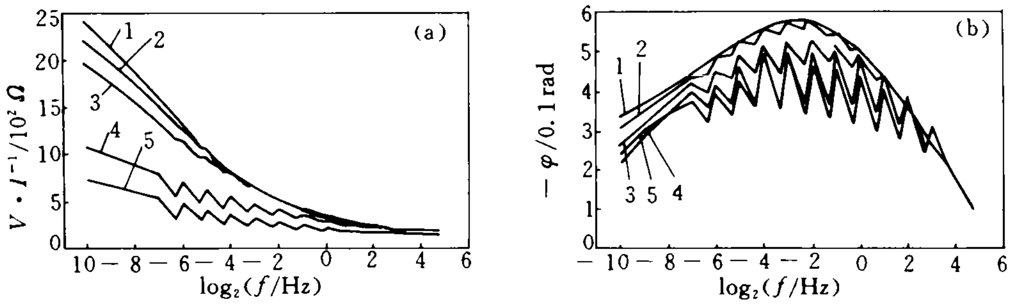

Fig. 5 **The dual-frequency IP spectral curves for chalcopyrite** ($24.5\,\mathrm{cm}^2 \times 4.1\,\mathrm{cm}$)

(a)—amplitude; (b)—phase

The current density in experiment for

curves 1~5 is 0.69, 2.63, 10.13, 50.77, 106.17 $\mu A/cm^2$, respectively

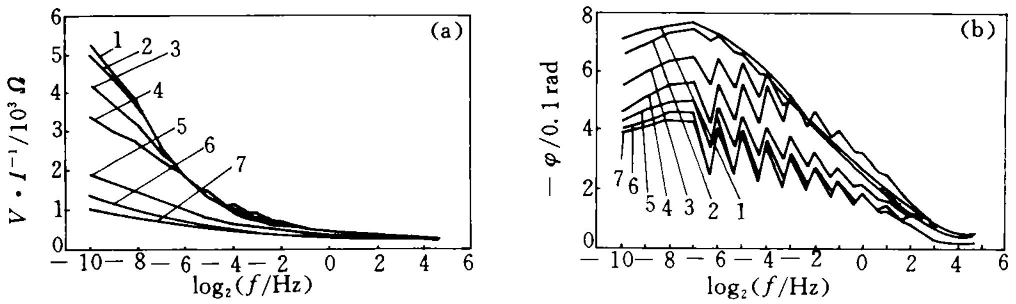

Fig. 6 **The dual-frequency IP spectral curves for magnetite** ($25.1\,\mathrm{cm}^2 \times 5.1\,\mathrm{cm}$)

(a)—amplitude; (b)—phase

The current density in experiment for

curves 1~7 is 0.17, 0.90, 3.43, 13.22, 41.63, 95.11, 138.48 $\mu A/cm^2$, respectively

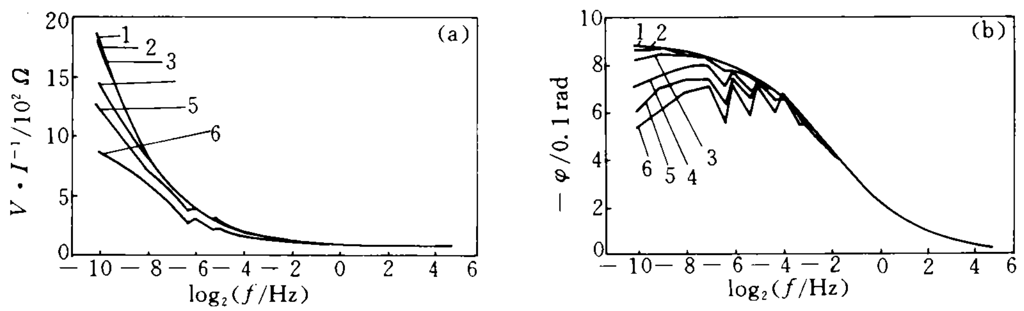

Fig. 7 **The dual-frequency IP spectral curves for graphite** ($28.5\,\mathrm{cm}^2 \times 3.2\,\mathrm{cm}$)

(a)—amplitude; (b)—phase

The current density in experiment for

curves 1~6 is 0.99, 3.95, 19.21, 47.88, 68.38, 116.54 $\mu A/cm^2$, respectively

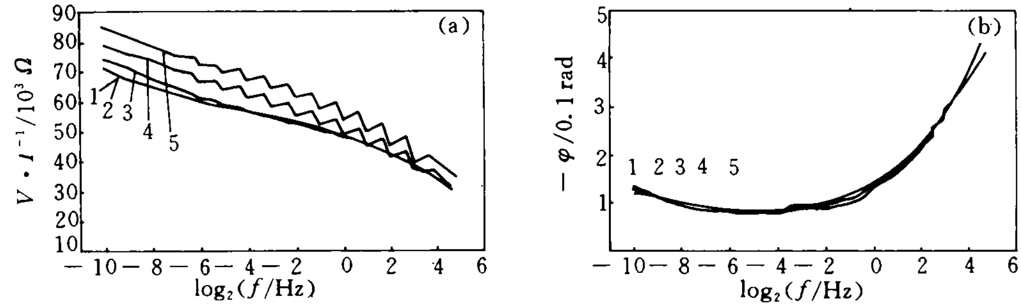

Fig. 8 The dual-frequency IP spectral curves for hematite (25.7 $\mathrm{cm}^2 \times$ 4.2 cm)

(a)—amplitude; (b)—phase

The current density in experiment for curves 1~5 is 0.55, 1.13, 2.25, 8.69, 16.07 $\mu A/cm^2$, respectively

× 3.0 m × 1.5 m. The dual-frequency IP method was used in the experiments. The experimental configuration is shown in Fig. 9.

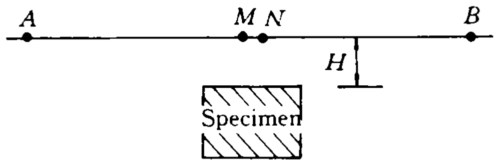

Fig. 9 The gradient configuration in 3-D water tank

(AB = 100 cm, MN = 1 cm, H = 3 cm)

Hz was firstly transmitted into the tank, then followed by another dual-frequency current of 2/13 Hz and 2 Hz. The receiver recorded the phases of the frequency of 2 Hz along a profile, respectively. Fig. 10 shows the experiment results measured with the gradient array. It is clear in the figure that the phases of the same frequency are different when it is transmitted as the basic and 13th harmonic frequency of the dual-frequency current. The specimen used in this experiment is made from pyrite, and the current density is about 10 $\mu A/cm^2$. The experiment was strictly carried out and it was impossible that this difference is caused by errors or personal reasons. As mentioned in the theoretical analysis, this kind of difference is a special phenomenon of nonlinear IP effect in the dual-frequeucy IP method. It is this difference leadig to produce the sawtooth feature in the dual-frequency IP spectral curves.

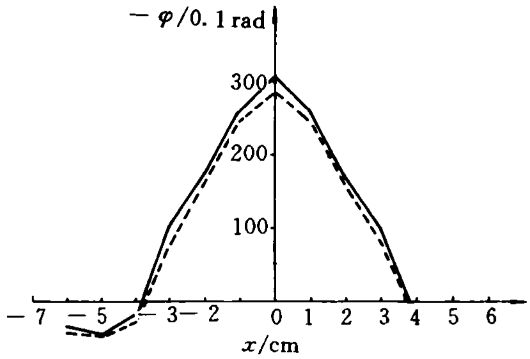

Fig. 10 The experimental results measured with gradient array

solid line—Basic frequency phase;

dashed line—13th harmonic frequency phase

2.3.2 Spectral Curves

Fig. 11 shows the dual-frequency IP spectral curves of a compact chalcopyrite and a graphite measured with the gradient array, respectively. After comparing these curves with those in Fig. 5 and Fig. 7, we can draw a conclusion that the sawtooth feature of IP nonlinear effect on spectral curves in 3-D case is similar to that in 1-D condition.

3 CONCLUSION

With the increasing of induced dual frequency current density, not only the total IP effect decreases, but also the sawtooth feature

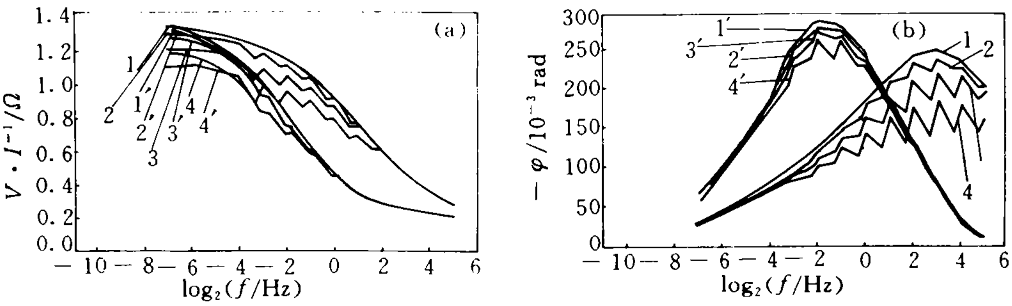

Fig. 11 **The dual-frequency IP spectral curves for both chalcopyrite specimens** (24.5 $\mathbf{cm}^2 \times 4.1$ **cm**) 1, 2, 3, 4 **and graphite specimens** (28.5 $\mathbf{cm}^2 \times 3.2$ **cm**) 1′, 2′, 3′, 4′, **measured in 3-D water tank**

(a)—amplitude; (b)—phase; The current density in experiment for curves 1~4 and 1′~4′ is 0.87, 4.70, 28.00, 63.54 $\mu A/cm^2$, respectively.

appears on the dual-frequency IP spectral curves. According to the theoretical analysis and experimntal results, this feature is caused by the difference of IP nonlinear effect of the same frequency transmitted as the basic and 13th harmonic frequency of the dual-frequency current. It is a special feature of the IP nonlinear effect in the dual-frequency IP method.

Both theoretical calculation and experiment results showed that the sawtooth feature on the IP spectral curves is different for different minerals. The sawtooth feature on phase spectral curves is more obvious than that on the amplitude spectral curves. For metallic sulfides and magnetite, the nonlinear sawtooth feature is obvious when the induced current density is about 1 $\mu A/cm^2$. As for the carbonaceous minerals such as graphite, the current density necessary for the appearance of the sawtooth feature is about 50 $\mu A/cm^2$. In addition, the sawtooth feature appears at higher frequencies for sulfides when the induced current density increases, but it will not appear at higher frequencies though the induced current density is very high for carbonaceous minerals. The nonlinear spectral curves for hematite are totally different from these two kinds of curves. Therefore, it is possible to evaluate the IP anomalies using the nonlinear spectral curves. In practice, the sawtooth feature is a good indicator of IP nonlinear effect, so it is possible to develop a new geophysical method to evaluate IP anomalies.

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(Edited by Lai Haihui)