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Current and voltage source induced polarization transients: a comparative consideration

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ABSTRACT

The article discusses the excitation of transient induced polarization responses using current and voltage sources. The first method has found a wide application in induced polarization surveys and—directly or indirectly—in the theory of the induced polarization method. Typically, rectangular current pulses are injected into the earth via grounding electrodes, and decaying induced polarization voltage is measured during the pauses between pulses. In this case, only the secondary field is recorded in the absence of the primary field, which is an important advantage of this method. On the other hand, since the current injected into the ground is fully controlled by the source, this method does not allow studying induced polarization by measuring the current in the transmitter line or associated magnetic field. When energising the earth with voltage pulses, the measured quantity is the transient induced polarization current. In principle, this method allows induced polarization studies to be done by recording the transmitter line current, the associated magnetic field, or its rate of change. The decay of current in a grounded transmitter line depends not only on the induced polarization of the earth but also on the polarization of the grounding electrodes. This problem does not occur when induced polarization transients in the earth are excited inductively. A grounded transmitter line is a mixed-type source; hence, for a purely inductive excitation of induced polarization transients, one should use an ungrounded loop, which is coupled to the earth solely by electromagnetic induction.

Key words: Induced polarization, Cole-Cole model, Transient response.

INTRODUCTION

In time-domain induced polarization (IP) studies, the earth is usually excited by rectangular current pulses (Sumner 1976; Komarov 1980). The measured quantity is the decaying IP voltage referred to in Wait (1982) as a “basic transient response”.

Figure 1 shows a simplified presentation of the conventional time-domain IP measurement arrangement. When the switch is closed, the current I flows in the circuit, and the earth is polarised. After the current turn-off, a decaying IP voltage $U_{\text{IP}}(t)$ between electrodes M and N is measured.

Obviously, at some instant of time preceding the current switch-off, the switch had to be closed, producing an IP transient upon decaying of which a steady current I_0 flows in the circuit. Usually, the internal resistance of a battery (or of a dc voltage generator) is low. Thus, when the switch is closed, a *voltage* source is connected to the electrodes A and B. However, when opening a switch at $t = 0$, the current instantaneously (on the measurement time scale) becomes equal to zero irrespective of the circuit parameters, including those of the battery, grounding, wire, and the earth. Figuratively speaking, when the circuit is broken off, there is nothing else left for the current to do but to become zero. At $t \geq 0$, the voltage $V_{\text{IP}}(t)$ across the electrodes M and N is the sum of voltages

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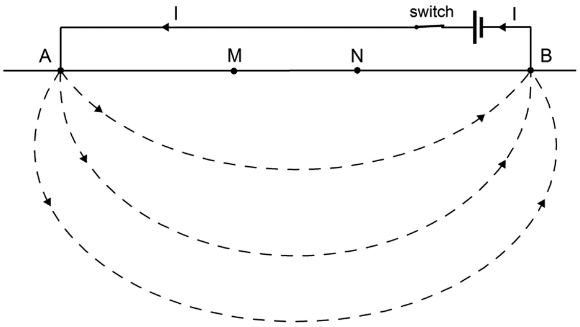

Figure 1 Simplified presentation of a time-domain IP measurement circuit.

produced by the steady current I_0 and a negative current step $I(t) = -I_0 u(t)$, where $u(t)$ is the Heaviside step function.

The above way of studying IP is not the only one. For example, one can excite a target using rectangular voltage pulses (Alvarez 1973; Shesternyov, Karasyov and Olenchenko 2003; Karasyov, Ptitsyn and Yuditskikh 2005) and measure IP transient current. Many scientific and technical publications on the nature of the IP phenomenon and its potential in geological applications are available in geophysical literature. These publications are based on an explicit or an implicit assumption on the use of current-source excitation. IP studies with the voltage-source excitation are usually not the subject of discussion. In this regard, it is expedient to compare both ways. Apparently, it is reasonable to begin with IP measurements on polarisable rock samples.

INDUCED POLARIZATION VOLTAGE RESPONSE OF A SAMPLE TO A RECTANGULAR CURRENT PULSE

Figure 2 shows a sample of a geological material connected in series with the current source. By definition, the internal resistance of an ideal current source is equal to infinity (Simonyi 1963). Practically, the internal resistance of a

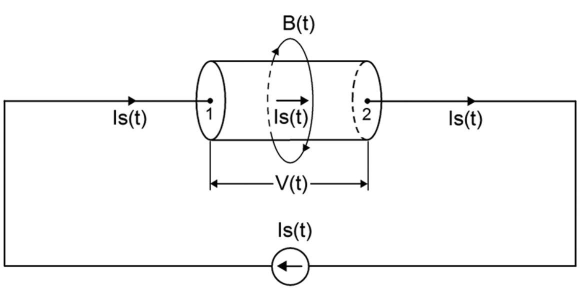

Figure 2 Current source connected to a rock sample.

current source must be as large as possible (in any case, much larger than the sample resistance). This means that the current $Is(t)$ passing through the sample is controlled by a source and does not depend on sample properties. Usually, the current source used in time-domain induced polarization (IP) studies generates rectangular current pulses alternating with pauses. The current pulses cause, across sample faces 1 and 2, IP voltage transients, $V(t)$.

Assume that at $t = 0$ the source instantly generates and then maintains current of I_0. Such current step of infinite duration can be presented as

$$I(t) = I_0 u(t). \tag{1}$$

If I_0 is equal to a unit current (e.g., 1 A), the voltage $V(t)$ between sample faces (see Fig. 2) represents a "voltage to the unit current step" transient response. We will designate it $F_I(t)$. For arbitrary I_0, $V(t) = I_0 F_I(t)$. The current Is, which is turned on at $t = t_1$ and switched off at $t = t_2$, can be written as

$$Is(t) = I_0 \left[u(t - t_1) - u(t - t_2) \right]. \tag{2}$$

According to the superposition rule, the transient voltage response to the pulse of current with amplitude equal to I_0 is

$$V(t) = I_0 \left[u(t - t_1) F_I(t - t_1) - u(t - t_2) F_I(t - t_2) \right]. \tag{3}$$

The resistance of a sample, R, is equal to $\rho\ l/A$, where ρ is the resistivity, l is the sample length, and A is the cross-sectional area. The resistance of a non-polarisable sample does not depend on frequency or time, i.e., is purely active. A non-polarisable sample exhibits no after-effect, and the voltage waveform repeats that of the current.

If the sample is polarisable, the current and voltage waveforms differ. Suppose that the sample resistivity is described by the Cole–Cole relaxation model (Pelton *et al.* 1978):

$$\rho^*(\omega) = \rho_0 \left\{ 1 - m \left[1 - \frac{1}{1 + (j\omega\tau)^c} \right] \right\} = \rho_0 \frac{1 + (1 - m)(j\omega\tau)^c}{1 + (j\omega\tau)^c}, \tag{4}$$

where $j = \sqrt{-1}$, ω is angular frequency, ρ_0 is dc resistivity, m is chargeability, τ is the IP time constant, and c is the exponent with limits 1 (a single relaxation) and 0 (an infinitely broad and continuous distribution). Chargeability m can be expressed as (Sumner 1976; Kulikov and Shemyakin 1978)

$$m = \frac{\rho_0 - \rho_\infty}{\rho_0}, \tag{5}$$

where ρ_∞ is the high-frequency limit of resistivity (in practice, ρ_∞ is resistivity at a frequency that is much higher than the relaxation frequency $\omega_\theta = 1/\tau$).

The reciprocal of equation (4) expresses the Cole–Cole relaxation model in terms of conductivity (Olhoeft 1979):

$$\sigma^*(\omega) = \frac{1}{\rho^*(\omega)} = \sigma_0 \frac{1 + (j\omega\tau)^c}{1 + (1 - m)(j\omega\tau)^c}, \quad (6)$$

where $\sigma_0 = 1/\rho_0$ is dc conductivity. When using conductivity representation of the Cole–Cole model, m is usually written as

$$m = \frac{\sigma_\infty - \sigma_0}{\sigma_\infty}, \quad (7)$$

where $\sigma_\infty = 1/\rho_\infty$ is the high-frequency limit of conductivity.

Let us find the current-to-voltage transient response for $c = 1$ (the Debye relaxation). In this case, simple algebra enables, without loss of generality, to get useful results. Clearly, for $c = 1$, equation (4) becomes

$$\rho^*(\omega) = \rho_0 \frac{1 - (1 - m) j\omega\tau}{1 + j\omega\tau}. \quad (8)$$

We find voltage $V(t)$ using the Laplace transform. When $t \le 0$, the current passing through the sample and the voltage between the sample faces are equal to zero. Because of zero initial conditions, Kirchhoff's laws apply to Laplace transforms of currents and voltages, as they apply to the complex currents and voltages in sinusoidal current circuits (Simonyi 1963).

In the frequency domain, we have

$$V(j\omega) = I(j\omega)R(j\omega) = I(j\omega)\rho_0 \frac{1 + (1 - m) j\omega\tau}{1 + j\omega\tau}. \quad (9)$$

Allowing a change in the last expression $j\omega$ to the complex variable s and given that the Laplace transform of the step current (1) is equal to I_0/s (Simonyi 1963), we have

$$V(s) = I_0 \frac{l\rho_0}{A} \frac{1 + (1 - m)s\tau}{\tau + 1/s}. \quad (10)$$

The inverse Laplace transform of $V(s)$ is

$$V(t) = I_0 \frac{l}{A\sigma_0}(1 - m\mathrm{e}^{-\frac{t}{\tau}}). \quad (11)$$

At $I_0 = 1\mathrm{A}$, the last expression defines the $F_\mathrm{I}(t)$ function:

$$F_I(t) = \frac{l}{A\sigma_0}(1 - m\mathrm{e}^{-\frac{t}{\tau}}). \quad (12)$$

Figure 3(a) shows a rectangular current pulse $Is = 10\ \mu\mathrm{A} \times [u(t - 0.5\ \mathrm{s}) - u(t - 1.5\ \mathrm{s})]$. The voltage response, $V(t)$, for the sample with $\rho_0 = 100\ \Omega\mathrm{m}$, $\tau = 0.1$ s, $m = 0.5$, $S = 10\ \mathrm{cm}^2$, and $l = 10$ cm is shown in Fig. 3(b). One can see in many articles and books on the IP method (Sumner 1976; Komarov 1980) plots such as in Fig. 3. Both in field and laboratory studies, the measured quantity is time-decaying voltage, $V_{\mathrm{IP}}(t)$.

We will denote the time constant of the transient IP voltage response to a current pulse as τ_{IS}. According to

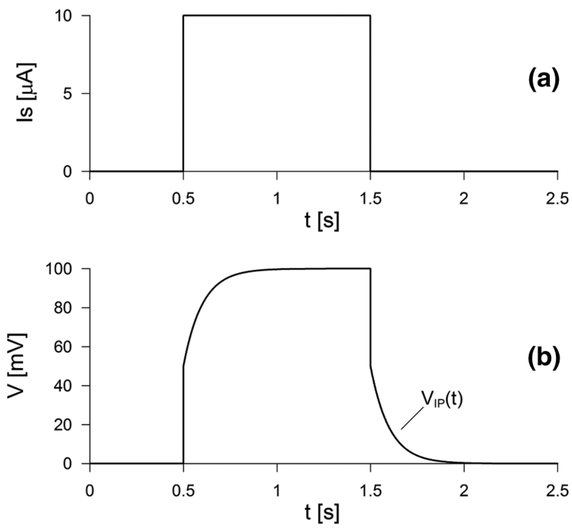

Figure 3 (a) Rectangular pulse of current and (b) voltage response. Parameters of the sample are $\rho_0 = 100\ \Omega\mathrm{m}$, $\tau = 0.1$ s, $m = 0.5$, $A = 10\ \mathrm{cm}^2$, and $l = 10$ cm.

equations (11) and (12), τ_{IS} is equal to the relaxation time constant τ of the Cole–Cole formulas (4) and (6).

The waveform of $V(t)$ is explained as follows (Sumner 1976). At any time, the current through the sample is equal to the sum of the conduction and the polarization (displacement or capacitive) currents. At the instants of on and off switching, the capacitive reactance and, accordingly, the total impedance of the sample are minimal. As capacitive reactance increases with time, the total impedance also increases; when $t \to \infty$, the total impedance is approaching the sample dc resistance. Since the current passing through the sample is completely controlled by the current source and because of zero initial condition, the $V(t)$ waveform follows that of the total impedance of the sample.

Considering excitation of the IP transient voltage with a current pulse, one gets insight into the feasibility of using this method for magnetic field measurements in IP studies. In the context of this article, it is logical to ask whether it is possible, by measuring the magnetic field of the current flowing in the circuit in Fig. 3, to determine the polarization parameters of the sample. Since, as already noted, the current in the circuit is completely controlled by the source, the magnetic field does not contain information about the properties of the sample. When the current is turned on, it is equal to I_0, and in the pauses between the pulses, $I(t) = 0$. This does not mean that there is no polarization current flowing through the sample. It is the *total* current that is either I_0 or zero.

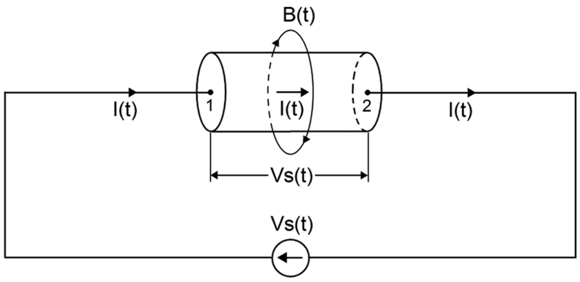

Figure 4 Voltage source connected to a rock sample.

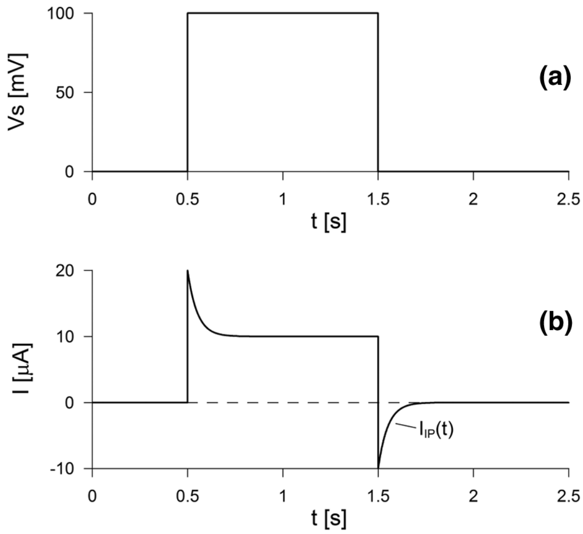

Figure 5 (a) Rectangular voltage pulse and (b) current response. Parameters of the sample are $\sigma_0 = 0.01$ S/m, $\tau = 0.1$ s, $m = 0.5$, $A = 10$ cm^2, and $l = 10$ cm.

Measurement of the magnetic field associated with IP currents in the earth forms the basis of the magnetic induced polarization (MIP) method (Seigel 1974). If measurements are made on the earth's surface, the MIP method is not suitable for studying the horizontally layered earth since the magnetic field does not depend on the vertical chargeability and resistivity profiles. As shown above, limitations of the MIP method manifest themselves also in the laboratory small-scale studies.

INDUCED POLARIZATION CURRENT RESPONSE OF A SAMPLE TO A RECTANGULAR VOLTAGE PULSE

Consider the response of a polarisable sample to a voltage source (Fig. 4). Suppose that the voltage at the source output is

$$V(t) = V_0 u(t). \tag{13}$$

If the voltage amplitude V_0 is unity (e.g., 1 V), the current $I(t)$ passing through the sample (see Fig. 4) may be defined as a "current to the unit voltage-step" transient response, $F_V(t)$. A rectangular voltage pulse with amplitude of V_0 (the voltage is turned on at $t = t_1$ and turned off at $t = t_2$) can be written as $Vs\,(t) = V_0\,[u(t_1) - u(t - t_2)]$. According to the superposition rule, the current response of a sample to the rectangular voltage pulse is

$$I(t) = V_0[u(t - t_1)F_V(t - t_1) - u(t - t_2)F_V(t - t_2)]. \tag{14}$$

According to Ohm's law, we have (in the case of $c = 1$, $j\omega = s$, and $V(s) = V_0/s$)

$$I(s) = \frac{V(s)}{R(s)} = \frac{V_0}{s}\frac{A}{l}\sigma_0\frac{1 + s\tau}{1 + (1 - m)s\tau}. \tag{15}$$

Using the inverse Laplace transform, we find

$$I(t) = \frac{V_0 A}{l}\sigma_0\left[1 + \frac{m}{1 - m}e^{-\frac{t}{\tau(1-m)}}\right]. \tag{16}$$

When $V_0 = 1$ V, this expression becomes the $F_V(t)$ function:

$$F_V(t) = \frac{1\,volt \cdot A}{l}\sigma_0\left[1 + \frac{m}{1 - m}e^{-\frac{t}{\tau(1-m)}}\right]. \tag{17}$$

The first term in equations (16) and (17) is conduction current; the second term is exponentially decreasing polarization current. As time elapses, the polarization current decays to a negligible value, and there remains only the conduction current. During the voltage pulse (Fig. 5(a)), the current in the circuit is the sum of the conduction and polarization currents (Fig. 5(b)). Upon removing the voltage (at $t = t_2$), the conduction current becomes zero, and the direction of the polarization current is reversed relative to that during the voltage pulse.

Considering the excitation of the induced polarization (IP) transient current with the voltage pulse suggests some special features of this method. First, according to equations (16) and (17), the time constant of transient IP current decay, τ_{VS}, is given by

$$\tau_{VS} = \tau(1 - m). \tag{18}$$

Thus, if $m > 0$, $\tau_{VS} < \tau$. When $m \to 1$, $\tau_{VS} \to 0$. In the above example (see Fig. 5), $\tau = 0.1$ s, $m = 0.5$, and $\tau_{VS} = 0.05$ s.

Another difference from the conventional IP method is that the transient current flowing through the sample *does depend* on σ_0, τ, and m. Thus, these parameters—at least in

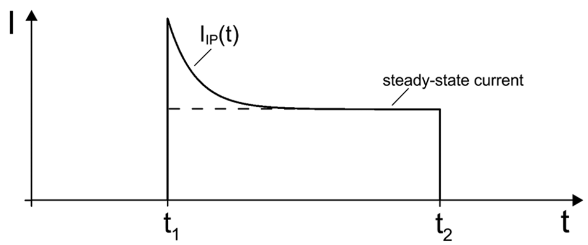

Figure 6 Current in the transmitter line of Fig. 1. On closing the switch at time t_1, the voltage step causes steady and transient IP currents to flow in the line. At time t_2, the switch opens, and the current in the line becomes zero.

principle—can be determined by measuring the current or the associated magnetic field.

As equations (16) and (17) indicate, when $m \to 1$, the IP current can be very large at early times.

INDUCTIVELY INDUCED POLARIZATION

Having considered the possibility of measuring the magnetic field of the induced polarization (IP) current made to flow in a sample by a voltage pulse, one might ask a question on how, using a voltage source, to excite the IP current in the earth.

When a switch in Fig. 1 is *closed*, the current in the circuit (lower half-space included), due to the low internal resistance of the battery, is set under the action of a voltage source. A general view of the current waveform is shown in Fig. 6. Shesternyov *et al.* (2003) and Karasyov *et al.* (2005) described and discussed IP studies based on recording the decaying current in a transmitter line.

It seems reasonable to assume that recording of the magnetic field produced by the transmitter line current will allow studying the IP of the earth. However, the practical implementation of this method may be complicated because transient current is affected not only by the earth but also by the polarization of grounding electrodes. Obviously, the less is the polarization of the electrodes the smaller is the error in inverted IP parameters of the earth.

Shesternyov *et al.* (2003) have shown that one can reduce this error by increasing the current passing through the electrodes during a voltage pulse. However, this does not solve the problem in principle, since the polarization of the electrodes is uncontrollable and its contribution to the total IP response is difficult to estimate, especially in field surveys. In studies of fast-decaying IP transients, an additional source of errors, especially at high grounding resistance, is the distributed capacitance of the transmitter line (Shesternyov *et al.* 2003). The same problem might appear in sample studies, although in this case, there may be more opportunities to control and reduce the electrode polarization effect.

When IP transients in the earth are excited using a simple circuit shown in Fig. 1, the voltage $V(t)$ between electrodes M and N is the convolution of the transmitter current with $F_I(t)$. Because of this, $V(t)$ depends on whether it is established when the transmitter current is turned on or off. This difference is insignificant at small chargeabilities but becomes more noticeable with increasing m. Figure 2.1 (p. 34) in Shesternyov *et al.* (2003) illustrates this effect. According to the literature on the time-domain IP method, IP voltage transients upon current switching on and off differ in sign but are otherwise identical. As follows from above, the identity is only possible if the target is excited by a current source during *both* turn-on and turn-off times.

When the transmitter current changes, the earth is excited both by galvanically driven current and electromagnetic induction. In turning on and off the transmitter current, the vortex electric field arises around the transmitter line. This field causes currents to flow in the earth. In the case of conductive non-polarisable earth, these currents are usually referred to as "eddy currents". If the earth is conductive and polarisable, IP currents add to the response, resulting in a phenomenon known as inductively induced polarization (IIP) (Kozhevnikov and Antonov 2012).

Having measured the magnetic field of IIP currents, one can, in terms of a certain model (Cole–Cole and the like), evaluate the polarization parameters of the earth. It is important that it is an electric field, which excites IP transients. In terms of the electrical circuit theory, this is equivalent to using a voltage source (Wait 1983).

A grounded transmitter line is a "mixed type" source: polarization not only arises due to electromagnetic induction but also responds to the galvanically injected current. Therefore, one can measure directly only the total IP response usually dominated by the galvanic component. This problem does not exist when exciting the earth with a "pure" magnetic-type source, usually an ungrounded horizontal loop. According to Marchant, Haber and Oldenburg (2013), IP phenomena produced by purely magnetic excitation can be referred to as magnetic source induced polarization.

Consider the inductive source excitation by the example of a conductive and polarisable ring, or toroid (Fig. 7), an "extended" version of a wire-filament circuit. Although this model does not allow quantitative estimates of the physical parameters of the ground, it has proven to be useful when getting an insight into the role of various physical processes

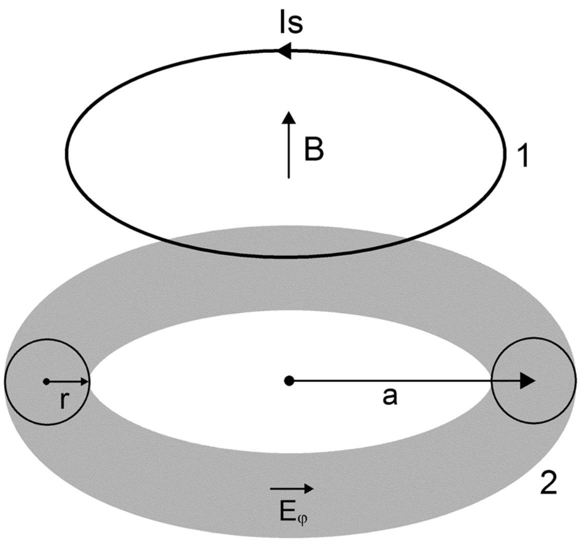

Figure 7 (1) Transmitter loop and (2) polarisable toroid.

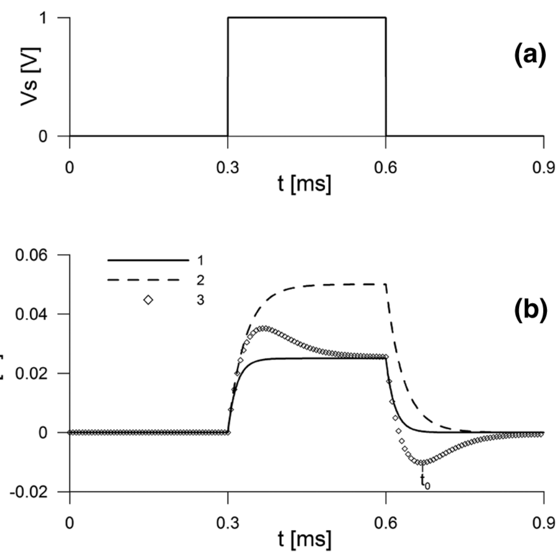

Figure 8 Simple illustration of the inductive source IP. (a) Voltage pulse induced in a toroid during the switching off of the primary magnetic field. (b) Current response for non-polarisable (1, 2) and polarisable (3) toroids.

(Grant and West 1965; McNeill 1980; Weidelt 1982; Smith and West 1988) and interpreting the transient electromagnetic (TEM) response of sheet-like conductors suspended in resistive bedrock (Barnett 1984; Boyd and Wiles 1984).

The ring is excited by a circular transmitter loop. The radii of the ring and its cross section are, respectively, a and r. Suppose that the loop is driven by a steady current I_0. At some instant, the current starts to decay linearly, the total turn-off time being Δt. Since the transmitter current and the associated primary magnetic field change synchronously, the current turn-off generates a rectangular pulse of the vortex electric field around the loop.

The electromotive force (EMF) acting along the ring during the current turn-off is

$$V = -M\frac{dI}{dt} = -M\frac{I_0}{\Delta t}, \tag{19}$$

where M is the mutual inductance between the loop and the ring.

Figure 8(b) shows waveforms of the current arising in the ring ($a = 50$ m, $r = 5$ m) in response to a rectangular ($\Delta t = 0.3$ ms) voltage pulse (Fig. 8(a)). Calculations were performed in the frequency domain, upon which they were transformed to the time domain.

Smith and West (1988) considered inductively induced transients in polarisable wire circuits with lumped parameters. Appropriate solutions have been found using the Laplace transform, which gives them undeniable elegance. However, this method is applicable only for a non-polarisable ($m = 0$) and two polarisable ($m \neq 0$, $c = 0.5$, $c = 1$) circuits. Methods based on numerical calculation enable solving the problem at any parameters of the ring.

The complex impedance of a ring at frequency ω is

$$Z^{*}(\omega) = j\omega L + R^{*}(j\omega) = j\omega L + \frac{2a}{\sigma^{*}(j\omega)r^{2}}, \tag{20}$$

where L is the inductance of a ring, $R^{*}(j\omega)$ is its complex resistance, and $\sigma^{*}(j\omega)$ is described by equation (4). The inductance of a ring depends only weakly on ω; for the above ring ($a = 50$ m, $r = 5$ m), the L value calculated using formula (5-2) in Kalantarov and Tseitlin (1986) is 1.65×10^{-4} H.

Plots 1 and 2 in Fig. 8(b) demonstrate the responses of a non-polarisable ($m = 0$) ring for both of the limiting conductivity values: $\sigma_0 = 0.1$ S/m and $\sigma_\infty = 0.2$ S/m. According to Macnae (2016), these two conductivity values are referred to as, respectively, "steady or direct current" and "electromagnetic inductive" limits. On turning-on as well as turning-off the primary electric field, the current decays exponentially with a time constant of 4 μs (direct current limit) and 8 μs (electromagnetic inductive limit). Typically, the quantity measured in the TEM prospecting method is EMF induced in the receiver loop by the secondary magnetic field, $B_2(t)$, upon switching off the transmitter current. In the case being considered (see Fig. 8), the transmitter current turns off at $t = 0.6$ ms. Because $B_2(t)$, like the current in the ring, decays monotonically, the polarity of the EMF remains constant.

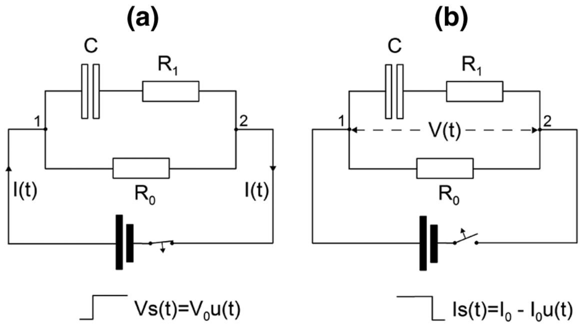

Figure 9 An equivalent circuit IP model excited by (a) step voltage and (b) step current sources.

Plot 3 in Fig. 8(b) illustrates the effect of IP on the induction transient response. With time, the current in the polarisable ($\sigma_0 = 0.1$ S/m, $m = 0.5$, $c = 0.9$, $\tau = 100$ μs) ring decreases; at $t = t_0$, it reaches a negative minimum and then increases, asymptotically approaching zero. Correspondingly, at $t = t_0$, the EMF induced in the receiver loop changes sign. As Fig. 8 indicates, the σ_∞ response follows more of the IP response directly after pulse turn-on.

The non-monotone waveform and sign change of TEM response predicted by the above simple model are characteristic of polarisable targets (Lee 1975; Weidelt 1982) and are observed in field surveys when studying polarisable geologic media, such as frozen sediments (Kozhevnikov and Antonov 2006, 2012) and rocks with enhanced concentration of electronically conductive ore minerals (Spies 1980).

DISCUSSION AND CONCLUSIONS

When exciting a sample with the voltage source, the current passing through the sample depends on its electrical properties. This makes possible induced polarization (IP) studies by recording the IP current or the associated magnetic field. In the case of current-source excitation, the time constant τ_{IS} of an IP voltage transient is equal to the τ of the Cole–Cole formula. As for the current IP response to a voltage source, the smaller the chargeability the greater the time constant: $\tau_{\mathrm{VS}} = \tau\,(1 - m)$.

Svetov and Ageev (1999) and Svetov (2008), having compared (for $c = 1$) the Cole–Cole formulas for resistivity ρ and conductivity σ, concluded that both formulas are equivalent provided the corresponding time constants (τ_ρ,τ_σ) are related as $\tau_\rho = \tau_\sigma/(1 - \mathrm{m})$. Commenting this result, the authors suggested that the difference in the time constants τ_ρ and τ_σ reflects the difference in decay of the IP processes in current when switching off the applied voltage (τ_σ) and, by contrast, in voltage when switching off the applied current (τ_ρ).

Tarasov and Titov (2013) compared the Cole–Cole formula for the frequency-dependent conductivity and the Pelton formula for the frequency-dependent resistivity (1978) and have showed that both formulations are equivalent if

$$\tau_{CC} = \tau_P (1 - m)^{1/c}, \tag{21}$$

where τ_{CC} is the time constant in the Cole–Cole formula for conductivity, and τ_{P} is the time constant in the Pelton formula for resistivity.

According to Tarasov and Titov, when experimental data are compared in terms of the Cole–Cole parameters, it is important to use the same model, especially for the cases where the chargeability values are high. Equation (21) presents the link between the two models and can be used to convert the relaxation time values from one model to the other.

However, as shown by Macnae (2015a), the Cole–Cole and Pelton models in fact require identical independent parameters that can fit experimental or synthetic data, provided the Pelton resistivity formulation is restricted to fitting to resistivity data, and the Cole–Cole conductivity formulation is restricted to fitting conductivity results.

A detailed discussion of the cited works is beyond the scope of our paper. Unlike the above authors, we give, using the Pelton formulation, a straightforward derivation of the expressions for the current-source and voltage-source IP transients and discuss them as applied to the time-domain IP studies.

We note only that in the original, or "classic", Cole–Cole formula for the dielectric relaxation, all the parameters are independent, whereas in the Pelton formulation for $\rho^*(\omega)$ and, respectively, for $\sigma^*(\omega) = 1/\rho^*(\omega)$, m and τ are coupled parameters linked through the ohmic conductivity σ_0 (Olhoeft 1979, pp. 10–13).

Let us discuss the current-source and voltage-source excitations using an elementary lumped circuit (Fig. 9) that one can find in many IP papers and books (e.g., Sumner 1976, p. 61). The circuit consists of a purely resistive arm R_0, representing the resistive ionic conduction in un-mineralised current paths near a metallic mineral. The resistor R_1 can represent the resistance due to blocked conduction paths within mineralised rock, and the capacitor C can be associated with the double-layer capacitance and Warburg impedance. The chargeability is given by the equation: $m = R_0/(R_0 + R_1)$.

A source consisting of a battery with the voltage of V_0 and a switch, connected in series, is connected to points 1 and 2 of the circuit, as shown in Fig. 9.

Suppose that the switch is closed at some moment of time. Since the internal resistance of the battery is small, upon closure of the switch, the capacitor is charged with a time constant $\tau_{VS} = CR_1$. Using elementary algebra shows that the total current in the circuit is given by

$$I(t) = \frac{V_0}{R_0}\left(1 + \frac{m}{1-m}e^{-t/\tau_{VS}}\right). \tag{22}$$

As shown in the introduction part of this paper, the opening of the switch is equivalent to the connection of the current source to points 1 and 2 of the circuit. In this case, the capacitor is discharged through resistors R_0 and R_1 connected in series. The discharge time constant is given by $\tau_{IS} = C(R_0 + R_1)$. The voltage decay across points 1 and 2 of the circuit is given by (Sumner 1976)

$$V(t) = V_0 m e^{-t/\tau_{IS}}. \tag{23}$$

As in the case of the Cole–Cole model, $\tau_{VS} = \tau_{IS}\,(1 - m)$.

Note that the difference between current-source and voltage-source IP transients exists on the physical level and can be observed experimentally. This difference does not affect the interpretation of the IP data because, when inverting them, one searches for the true Cole–Cole parameters that fit the data.

Of the two ways of excitation (namely, with a current or a voltage source), the first one has found wide use in the IP studies. Its principal advantage is that IP transients are measured during pauses between the current pulses, that is, in the absence of the transmitter current. This, among other things, eliminates the effect of polarization of the transmitter line electrodes on the IP signal. Another factor that might have contributed to the wide application of the current-source excitation is that in the pauses between current pulses, there is no need of using special electronics to keep the current constant: opening the switch in Fig. 1 is equivalent to the action of an ideal source, creating a negative current step.

In principle, exciting the geologic material with voltage pulses allows IP studies to be made by recording the current and its magnetic field (or the rate of magnetic field change). When the switch in the circuit in Fig. 1 is closed, the battery acts as a voltage source. We have illustrated the voltage-source excitation as applied to the studies of polarisable samples (see Figs. 4 and 5). Shesternyov *et al.* (2003) used records of the transmitter line current in laboratory studies of frozen rock samples. Karasyov *et al.* (2005) described the results of applying this method to search for IP anomalies associated with ore bodies. Although the potential of the method in studies of horizontally layered polarisable earth is currently not clear, it is reasonable to assume that such parameters of the layers as chargeability and relaxation time should influence the decay of a current passing through the transmitter line.

In field IP surveys (see Fig. 1) or in IP studies on samples (see Fig. 4), the voltage source can be good but, in contrast to the current source, not ideal yet. The reasons that do not allow creating an ideal voltage source are the non-zero internal resistance of the battery, grounding impedance, resistance, capacitance, and inductance of the wire. Among these factors, the most important is the grounding impedance, which, because of spontaneous and induced electrode polarization, is complex, time dependent, and non-linear.

Evidently, the polarization of grounding electrodes does not occur in the inductive mode excitation. A grounded transmitter line is the source with mixed mode of excitation (Kulikov and Shemyakin 1978; Mogilatov 2012). Because of this, it is better to use an ungrounded loop, which is coupled to the earth purely inductively. Using an ungrounded loop or coil as the receiver removes also the problem caused by the polarization of measuring electrodes. Additional advantages are that the inductive source is insensitive to transverse anisotropy and enables studying targets under non-conductive strata (Kaufman and Keller 1983).

As an approximation, the currents arising in the earth upon the sudden change in the primary magnetic field represents the sum of eddy currents, controlled by the conductivity distribution, and polarization currents. In general, transient current, even in the simple models, is a single process not predictable using the superposition principle (Smith and West 1988). This limits the applicability of approximate methods of interpretation, based on the assumption that IP and induction responses are additive (Kamenetsky, Trigubovich and Chernyshev 2014).

Obviously, the general approach to the interpretation of the transient electromagnetic (TEM) response with regard to IP is the use of complex, frequency-dependent conductivity, $\sigma^*(\omega)$. Inversion of the induction transients in terms of horizontally layered earth with $\sigma^*(\omega)$ described by the Cole–Cole model has become a routine procedure (Kozhevnikov and Antonov, 2008; Antonov, Kozhevnikov and Korsakov 2014; Kozhevnikov *et al.* 2014; Seidel and Tezkan, 2017). Some publications report on the inversion of TEM responses in terms of the three-dimensional distribution of frequency-dependent conductivity (Marchant *et al.* 2013; Marchant, Haber and Oldenburg 2014). In recent years, great progress has been made in the quantitative interpretation of airborne TEM surveys by taking into account the IP effects (Macnae 2015b, 2016; Viezzoli and Kaminski 2016).

The method of IP with inductive source excitation has its own limitations. In the traditional IP method, IP transients are excited by the pulse current injected into the ground via grounded electrodes, and the measurements are performed at late times, after the induction process has decayed. In this case, a "purely" IP response is measured.

As for inductive source IP, its effect on the total TEM response depends on both properties of the earth and parameters of the TEM configuration. Thus, changing the thickness *h* of a conductive and polarisable layer, overlying a non-polarisable resistive base, results in a significant change in the manifestations of inductively induced polarization (IIP) (Kozhevnikov and Antonov 2009). Other things being equal, there is a range of *h* over which the TEM prospecting method is advantageous for detection and study of the polarisable layer. Outside this range, the IIP effect is small, and the inverse solution becomes ambiguous. Hence, the efficiency in the use of the TEM prospecting method in IIP studies depends on the target geometry and properties. This inference is not unexpected, as any geophysical method occupies its "place". Recall that, traditionally, the TEM prospecting method and its analogue, the TEM sounding method, have wide application in the search for and study of targets with high conductivity (McNeill 1980). There is little sense in using these methods in the search for a thin resistive layer, even more for estimating its parameters. On the other hand, these methods are adequate when the object of study is a conductive layer in a resistive environment.

Sometimes, a combination of several grounded lines (Kulikov and Shemyakin 1978; Mogilatov 2012; Mogilatov, Zlobinskiy and Balashov 2016) or loops (Spies 1975) is used to energise the earth. Such sources suppress the contribution of the horizontally layered medium to the total transient response and enhance the effect of two- and three-dimensional structures. As can be inferred from available publications, there has been no discussion on the use of these sources in relation to the IP studies.

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