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The Antenna Polarization Effect in Transient Electromagnetic Sounding

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Abstract—An ungrounded loop is used as receiving and transmitting antennas in pulsed induction survey (the transient electromagnetic method). The traditional theory of this method does not take into account the electric characteristics of real antennas, considering them as abstract mathematical loops in which electric currents flow or electromotive forces arise. This approach is effectively applied to media with frequency-independent electric properties. However, effects arising in polarizing media can only be described through the analysis of frequency and transient responses of antennas as systems with distributed parameters. The antenna polarization effect arising in antennas with distributed resistivity and capacitance is analyzed. This effect produces the so-called "negative anomalies" at later stages of transient processes and decreases the efficiency of studies.

INTRODUCTION

The transient electromagnetic method (TEM) is applied to the response of geological media to a pulsed magnetic field. In geophysical practice, the transmitting and receiving antennas are usually represented by isolated wires that are laid on the surface in the form of square loops a few to a few hundred meters in size. Rectangular current pulses are fed to the transmitting antenna, and the response of the medium is observed via the receiving loop. The effectiveness of investigations can be increased by utilizing a single-loop variant of sounding, in which the same antenna is used for both transmitting magnetic pulses and recording the transient field response. The recorded transient responses, being functions of time, contain information on the resistivity distribution in the rock mass studied.

Theoretical and experimental data show that transient responses in the single-loop sounding are described by functions monotonically decreasing with time whose polarity does not change throughout their time range. A monotonic decrease is also characteristic of any time derivative of the transient response. This is valid for arbitrary media with frequency-independent electric and magnetic properties.

In practice, the transient responses (or their time derivatives) often change polarity due to the frequency dependence of the electrical conductivity of rocks. These effects are called "negative anomalies" in the induction survey.

Theoretically, it is easy to calculate the transient responses of horizontally layered media in which the conductivity is described by a complex-valued frequency-dependent function. Comparison of these calculations with experimental data reveals the presence of divergences that are often inconsistent with the model of a polarizing medium. These divergences cannot be accounted for in terms of the horizontal inhomogeneity of the medium or the imperfection of modeling techniques. It is clear that interpretation algorithms in these cases encounter insurmountable difficulties. The present work is devoted to the theoretical and experimental study of this phenomenon, known as the antenna polarization (AP) effect.

ASYMPTOTIC BEHAVIOR OF THE TRANSIENT RESPONSES IN THE NEAR-FIELD ZONE

In the case of inductive excitation of nonmagnetic media, the magnetic field $H(r, p)$ on the surface of a homogeneous half-space can be represented in the range of small parameters $|\mu_0 \sigma p r^2| \longrightarrow 0$ as the series [Kamenetsky, 1997; *Elektrorazvedka* ..., 1989]

$$H(r, p) = H_0(r) + p\sigma h(r) + \dots \quad (1)$$

Here, r is the distance of the measurement point from the source, $p = s + j\omega$ is the complex frequency, σ is the resistivity, and $\mu_0 = 4 \times 10^{-7}$ H/m.

The first term of the expansion $H_0(r)$ describes the primary field, independent of the conductivity, and the second term accounts for the part of the secondary field corresponding to the so-called small parameter range. This term characterizes the behavior of the field near the source. The terms of higher orders in p are omitted because their contribution to the transient response accounts for components that are more rapidly attenuated with time.

The above expansion holds in all of the known, analytically solved geoelectric problems. Below, we assume that it is valid in any, however complex, medium, and the conductivity of the medium is under-

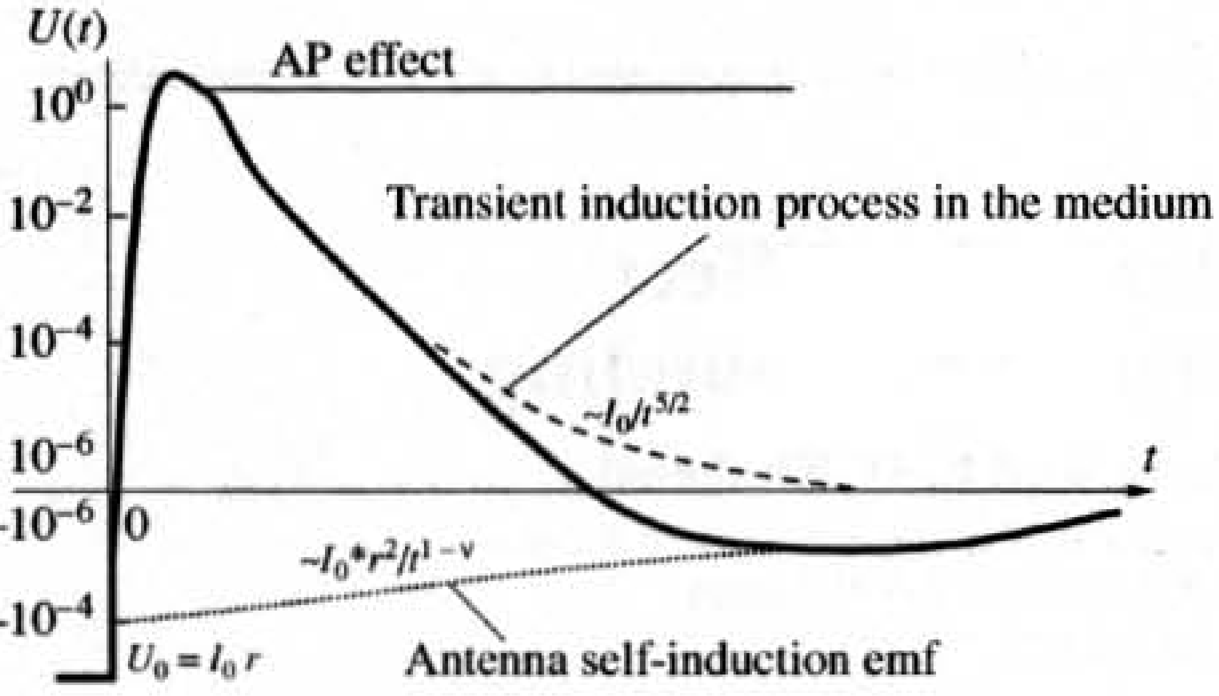

Fig. 1. Transient response in a combined receiving–transmitting antenna above a polarizing geological medium (a schematic illustration). I_0 is the antenna current, r is the antenna d.c. resistance, and $\nu > 0$. Positive and negative potentials are shown on a logarithmic scale, with a zero level of $\pm 10^{-6}$.

stood as a certain averaged (effective) parameter. Note also that, if σ is frequency independent, the term $p\sigma h(r)$ has no effect on the behavior of transient field responses at later stages, when $t/\mu_0\sigma r^2 \longrightarrow \infty$, and the field in this case is determined by the third term of the expansion [Kamenetsky, 1997]. We address some limiting cases of the frequency dependence $\sigma(p)$.

As is known from experiment and the theory of the classical method of induced polarization [Kormiltsev, 1980], the voltage U arising at receiving electrodes when a unit step current $1(t)$ is transmitted through a polarizing medium increases as $U(t) \sim \ln(t)$. In the frequency domain, this corresponds to a resistivity dependence $\rho(p)$ of the type

$$\rho(p) = 1/\sigma(p) \sim -\ln(p). \qquad (2)$$

Substituting in (1) the frequency-dependent conductivity from (2) and using the Stieltjes formula, we obtain the exponential spectrum [Svetov and Barsukov, 1979]

$$\begin{aligned} H(r, s) &= j/2\pi[H(r, se^{j\pi}) - H(r, se^{-j\pi})] \\ &= [\ln^2(s) + \pi^2]^{-1}. \end{aligned} \qquad (3)$$

The pulsed response of the magnetic field (the response to the δ function) corresponding to the product $p\sigma(p)$ can be found as the integral of the exponential spectrum

$$\begin{aligned} H(r, t) &= d/dt\int_0^\infty H(r, s)e^{-st}ds \\ &= -\int_0^\infty [s/(\ln^2(s) + \pi^2)]e^{-st}ds. \end{aligned} \qquad (4)$$

Since $H(r, s)$ varies very weakly in a wide range of s ($0 < H(r, s) <$ const at $st \gg 1$), we may state that $H(r, t)$ decreases with $t \longrightarrow \infty$ more rapidly than $1/t^2$.

A similar result ($H(r, t) \sim 1/t^{2+\nu}$) is obtained if the frequency dependence of the conductivity $\sigma(p)$ is determined by the Cola-Cola model [Kamenetsky, 1997]:

$$\sigma(p) = \sigma_\infty + (\sigma_0 - \sigma_\infty)/[1 + (p\tau_0)^\nu], \qquad (5)$$

where σ_0 and σ_∞ are the conductivities at low and high frequencies, τ_0 is a constant, and $0 < \nu \le 1$ is the logarithmic rate of relaxation. $H(r, t)$ decreases exponentially at $\nu = 1$.

Thus, we may state that, at any frequency dependence $\sigma(p)$, transient responses of the magnetic field excited by a magnetic source (dipole or loop) cannot decrease more slowly than $1/t^2$ at sufficiently large times $t \longrightarrow \infty$. This statement is also valid for the emf induced in a magnetic antenna, with the magnetic field excited by a step function $1(t)$ or $1 - 1(t)$.

NEGATIVE ANOMALIES OF THE TRANSIENT RESPONSES

Figure 1 illustrates schematically the electromagnetic (transient) response in a receiving–transmitting antenna typical of polarizing rocks. The voltage at the antenna terminals is $U(t) = -U_0$ until the turnoff ($t \le 0$), after which an antenna self-induction emf peak is observed in accordance with the Faraday law; this peak depends weakly on the structure of the medium and is determined by the distributed electrical parameters of the antenna in the high-frequency range (hundreds of kilohertz). This peak is followed by a transient characteristic containing information on the medium studied. Finally, later stages are characterized by a process coinciding in polarity with the voltage at the antenna terminals that existed before the turnoff of the current. This process can be of the following two types.

(1) The inductive processes are distorted by the complex resistivity, for example, of type (5) and can acquire "negative polarity." They are proportional to the current in the transmitting antenna and are independent of the resistivity of the antenna wires. As shown above, they decrease with time more rapidly than $\sim 1/t^2$ regardless of the frequency dependence of the conductivity. Such effects are called induced polarization (IP) or low-frequency dispersion [Kamenetsky, 1997]. TEM data complicated with IP effects can be interpreted applying usual inversion algorithms developed for models with a complex conductivity $\sigma(p)$.

(2) The processes have a negative polarity and decrease with time much more slowly than $\sim 1/t^2$ (commonly $\sim 1/t^{0.3-0.7}$). Their amplitudes depend on the type and resistivity of antenna wires, position of the antenna on the Earth's surface, humidity, and other factors. TEM data complicated with such processes cannot be interpreted by traditional methods. These processes are not of magnetic induction origin, but due to other physical factors.

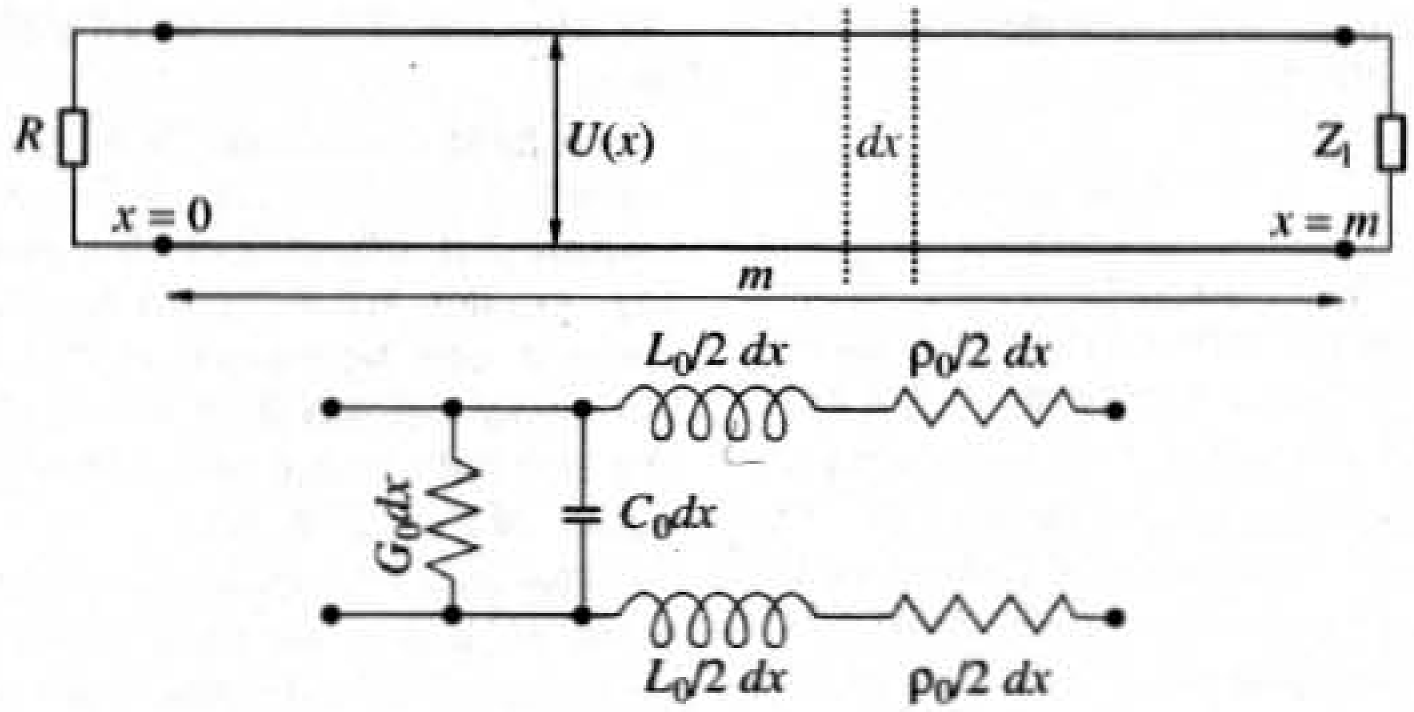

Fig. 2. Schematic illustration of a segment of the line with distributed parameters.

To gain an insight into this phenomenon, we will analyze the behavior of an antenna placed in a polarizing medium and possessing distributed electric parameters. In a first approximation, we may assume that the square or rectangular antenna usually employed in TEM sounding can be represented as a double-wire line, for which an analytical technique suitable for our case has been developed in electrical engineering.

DOUBLE-WIRE LINE WITH DISTRIBUTED PARAMETERS

Figure 2 schematically presents such a line of length m with distributed specific capacitance C_0 (F/m), inductance L_0 (H/m), resistance ρ_0 (Ω/m), and leakage conductance G_0 ($(\Omega/\mathrm{m})^{-1}$) and the equivalent electrical circuit of its element dx. The parameters C_0 and G_0 include the capacitance and leakage conductance of the antenna itself and the effect of the antenna interaction with the underlying medium. A resistance R is connected to the point $x = 0$ (input) of the line, and an impedance Z_1, to the point $x = m$.

We assume that the line is closed at its end (current loop), $Z_1 = 0$; the leakage resistance is negligibly small, $G_0 \longrightarrow 0$; and the parameters C_0, L_0, and ρ_0 are constant along the line (a homogeneous line and a horizontally homogeneous underlying section). The voltage $U(x)$ and the current $I(x)$ at any point are interrelated through the differential equations [Simonyi, 1956]

$$-dU/dx = L_0 dI/dt + \rho_0 J, \quad -dI/dx = C_0 dU/dt. \qquad (6)$$

We also assume that the variation rates of currents and voltages in the line are sufficiently small and that the following relation holds true:

$$\rho_0 J \gg L_0 dI/dt. \qquad (7)$$

For example, given a 1-mm^2 copper wire with the resistivity $\rho_0 = 1.7 \times 10^{-2}$ Ω/m and inductance $L_0 \times 10^{-6}$ H/m, we have $\rho_0/L_0 \sim 4 \times 10^3$ s^{-1}, and relation (7) holds at a current variation rate $I^{-1}dI/dt < 4 \times 10^3$ s^{-1}, which corresponds to frequencies $f \le 10$ kHz.

Let all transient processes in the line be over by the time moment $t = 0$ and let a direct current I_0 having the same value in any element of the line dx flow through the line. Evidently, the voltage at any point of the line is $U(0, x) = U_0(1 - x/m)$, where $U_0 = I_0 r$ and $r = 2m\rho_0$ is the d.c. resistance of the line. We determine the voltage existing in the line after the current turnoff at time moments $t > 0$, provided that the input resistance is $R \gg r$ (the line is open at its input). Omitting the well-known transformations [Simonyi, 1956], the solution of the problem as a function of the complex frequency $p = s + j\omega$ at the line input $x = 0$ can be written in the Laplace image domain as the series

$$U(0, p) = U_0 \sum A_k/(p + a_k^2/\tau), \qquad (8.1)$$

where $\tau = \rho_0 C_0 m^2$, $A_k = [1 + (-1)^k a_k]/a_k^2$, and $a_k = \pi(2k + 1)/2$, $k = 0, 1, 2, \ldots$). The time-domain original of (8.1) has the form

$$U(0, t) = U_0 \sum A_k \exp(-a_k^2 t/\tau). \qquad (8.2)$$

Series (8.1) and (8.2) converge rather rapidly at $a_k^2 t/\tau \ge 1$ and $p < a_k^2 t/\tau$, and the first term alone can be retained at long times and low frequencies:

$$U(p) = U(0, p) \approx U_0 A_0/(p + a_0^2/\tau), \qquad (9.1)$$

$$U(t) = U(0, t) \approx U_0 A_0 \exp(-a_0^2 t/\tau), \qquad (9.2)$$

where $A_0 = [1 + a_0]/a_0^2$ and $a_0 = \pi/2$.

In nonpolarizing media, the time constant of the antenna capacitance discharge is negligible, $\tau/(\pi/2)^2 \sim 10^{-9}$–$10^{-8}$ s. and the relaxation processes have no significant effect at $t > 1$ μs.

Now, we address a medium with a frequency-dependent permittivity. Let the distributed capacitance of the antenna (intrinsic and induced by the medium) be defined as $C(p) = D\varepsilon(p)$, $p = s + j\omega$, and depend on frequency as [Pelton *et al.*, 1983]

$$\varepsilon(p)/\varepsilon_0 = \varepsilon_\infty + (\varepsilon_s - \varepsilon_\infty)/[1 + (p\tau_0)]^\nu, \quad (10)$$

where $\varepsilon_0 = 10^{-9}/36\pi$ (F/m) is the permittivity of vacuum, ε_∞ and ε_s are the relative permittivities at high and low frequencies ($\varepsilon_\infty < \varepsilon_s$), D is a geometric factor measured in meters, τ_0 is the relaxation time constant, and $1 \geq \nu > 0$ is the so-called logarithmic decay rate. The case $\nu = 1$ yields the classical formula of Debye for the permittivity dispersion [King and Smith, 1981]. We also assume that the time constant τ_0 is much greater than $\tau/(\pi/2)^2$ from (9.2). Substituting the frequency-dependent capacitance (10) into $mC_0 = D\varepsilon(p)$ from (9.1) and applying the inverse Laplace transformation, we obtain the transient response

$$U(t) \approx I_0\, r^2\Delta\nu/\tau_0 \exp(-t/\tau_0)\cdot(\tau_0/t)^{1-\nu}, \quad (11)$$

where $\Delta = C(0) - C(\infty)$ is the dispersion relation, $C(\infty) = D\varepsilon_0\varepsilon_\infty$ and $C(0) = D\varepsilon_0\varepsilon_s$ are the capacitances at high and low frequencies, and $r = 2m\rho_0$ is the antenna d.c. resistance. The voltage $U(t)$ coincides in phase with the potential drop U_0 at the antenna wires at the time moment of the current flow and is opposite in phase with the self-induction emf (Fig. 1). Formula (11) describes the AP effect arising in an antenna with distributed parameters placed in a medium with a frequency-dependent permittivity. As seen from (11), the voltage at the antenna terminals is proportional to the squared resistivity of the antenna wires $\sim r^2$. Formula (11) includes the dispersion relation Δ, characterizing the polarizing medium. In the frequency-independent case, when $C(\infty) = C(0)$, no voltage arises in the antenna.

We estimate the effect for a typical antenna of 50 × 50 m in size with $r = 4\ \Omega$. In dry weather, we have for surface loams at $t = 1$ ms: $C(\infty) = 1000$ pF, $C(0) = 5000$ pF, $\nu = 0.35$, $\tau_0 = 10$ ms, and $U/I_0 \approx 1\ \mu$V/A.

Under conditions of a high air humidity (rain or dewfall), the antenna capacitance (the geometric factor D) increases by 5–7 (occasionally, 10) times due to the presence of a conducting water film on the surface of the insulating layer of wires, so that the effective distance from the conducting filament of the wire to the Earth's surface decreases to the thickness of the insulating layer. With the same parameters, the amplitude of the AP effect increases to $U/I_0 \approx 5$–$10\ \mu$V/A.

In sounding of permafrost rock masses, antenna capacitances slightly increase, the time constant τ_0 drops to 10–15 μs, and the exponent ν is close to unity. Under these conditions, anomalies are observed at early times: $U_{t=20\,\mu s}/I_0 \approx 1000\ \mu$V/A.

If the resistivity of the upper part of the section under study is sufficiently high (>1000 Ω m), inductive processes are weak and the negative anomalies appear as a negative half-wave at times of 10–100 μs. At later times, the inductive processes exceed in amplitude the AP effect, and the observed signal again becomes "positive."

In field conditions, it is easy to verify whether the recorded negative anomalies are the AP effect or the ordinary IP effect. For this purpose, the resistance of the antenna wire should be changed (for example, a resistor can be placed at the middle of the antenna perimeter). If this does not change the observed signal, the anomaly is due to the IP effect; otherwise, it is evidence of the AP effect.

The above formulas were derived for homogeneous lines. However, we established experimentally that the capacitance of antennas employed in practice depends weakly on the configuration of wires, provided that the antenna is located near the Earth's surface. With a given length of the perimeter, antennas shaped as a double-wire line (with a wire spacing of 1–2 m) and as a symmetrical dipole with the source at its center have capacitances coinciding within 5%. The distance to the surface in the experiments did not exceed 1 m, and the antenna perimeters were varied from 40 to 400 m. Therefore, one may suppose that the distributed capacitance of square and rectangular antennas is homogeneous along the perimeter and that the relations presented above are valid for these antennas as well.

A number of in situ experiments were carried out in order to check the theoretical results and estimate the actual values of the parameters τ and Δ.

EXPERIMENTAL STUDIES

The specific capacitance of a line located above an interface (Fig. 2) is determined by the formula [Iossel *et al.*, 1981]

$$C_0 = \pi\varepsilon_1/[\ln(d/a) + k\ln(d/2h)], \quad (12)$$

where a is the wire radius, h is the distance to the interface, d is the distance between the parallel wires, $k = (\varepsilon_1 - \varepsilon_2)/(\varepsilon_1 + \varepsilon_2)$ is the reflection coefficient, and ε_1 and ε_2 are the permittivities of the first and second media. With a sufficiently large value of d, we have $C_{01} = \pi\varepsilon_0/\ln(d/a)$ for an antenna in the air and $C_{02} = \pi\varepsilon_2/\ln(d/a)$ for an antenna in the ground. The capacitance of an aerial antenna is frequency independent because the air permittivity is close the vacuum value, but the permittivity of ground (rocks) appreciably differs from ε_0 and is always frequency dependent [Pelton *et al.*, 1983; King and Smith, 1981].

During the field experiments, the transient responses of isolated square antennas of various sizes were compared. The antennas were either located above the surface ($h \sim 0.5$–2 m) or buried at depths of ~0.2–0.3 m. Calculations showed that, if the side of an antenna exceeds its elevation above the ground by more than 20 times, the induction processes in the antenna are virtually independent of h. This suggests that the induction-related transient responses in antennas elevated above and buried in the ground coincide.

Figure 3 presents three transient responses obtained in experiments with a receiving–transmitting antenna. In all of the cases, the current amounted to $I_0 = 1$ A and the leakage resistance was no less than 25 MΩ. The 400-Hz capacitances between the wires at the middle of the loop perimeter were 1000 (A), 8400 (B), and 8450 (C) pF. The antenna inductance was 460 μH. The ground was composed of relatively dry loams.

All the three processes are similar at times $t < 200$ μs; at $t > 600$ μs, the process in the elevated antenna retains its polarity, whereas the polarity becomes inverted in the buried antennas. The process observed in the experiment with the 6-Ω wire antenna elevated above the surface coincided completely with variant A and is not shown in Fig. 3. The AP effect is clearly seen to depend on the antenna wire resistance (see curves B and C). According to (11), a rise in the wire resistance from 4 to 6 Ω should increase the resulting signal by about 2.5 times, and this is actually observed in the experiment. Although this example clearly illustrates the AP effect, it does not provide an estimate of the dispersion relation Δ, because the recording time interval is too narrow to determine the relaxation time constant τ.

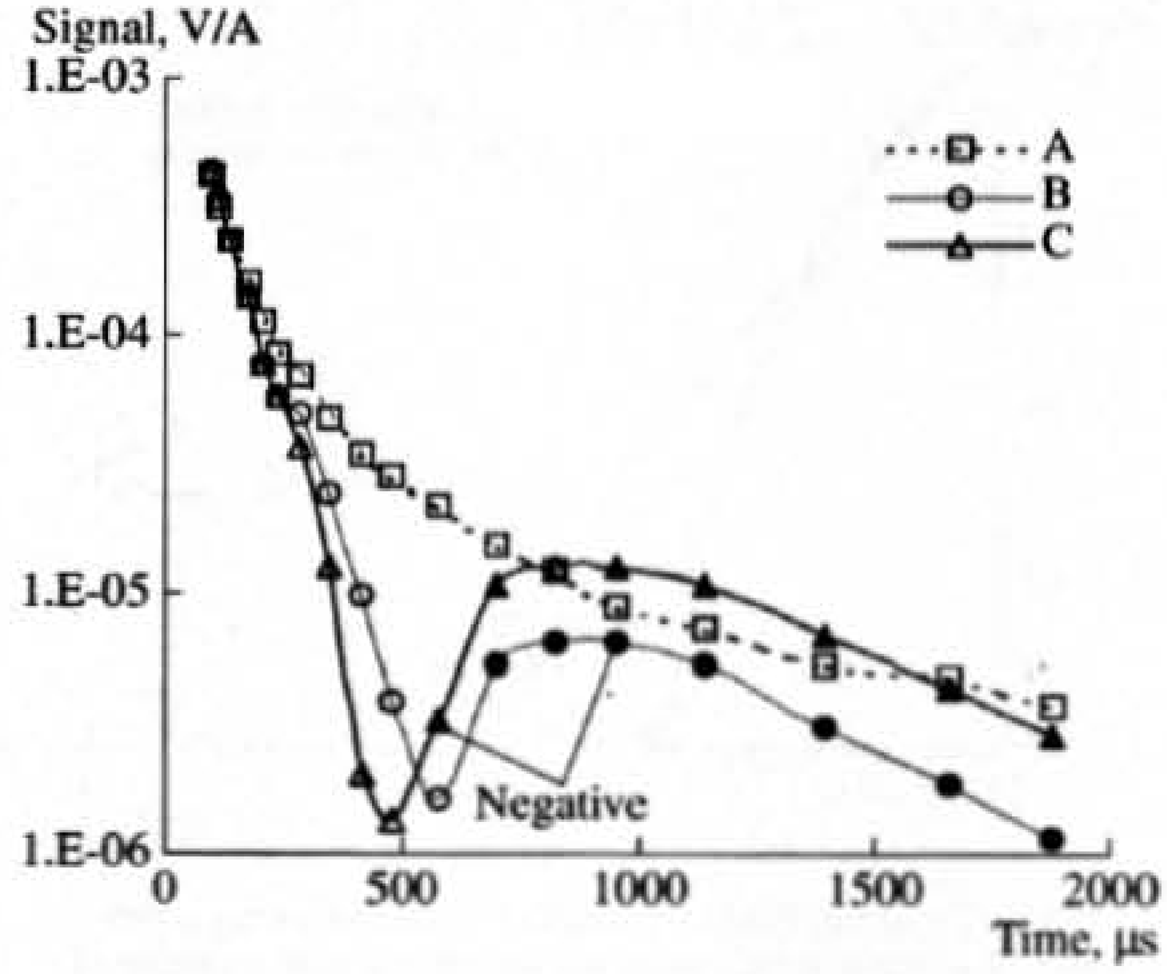

Fig. 3. Transient responses in a combined receiving–transmitting 50 × 50-m antenna: (A) wire resistance is $r = 4$ Ω and the antenna is 1 m above the loam surface; (B) $r = 4$ Ω and the wires are buried in loam at a depth of 20 cm; (C) $r = 6$ Ω with an antenna burial depth of 20 cm.

Figure 4 presents the normalized characteristic of the AP effect obtained in a 50 × 50-m antenna buried in wet clay. The normalization consisted in the removal of the induction process observed in the antenna 2 m above the clay from the recorded signal. The capacitance of the antenna buried in the clay was ~7600 pF (~1000 pF in the elevated antenna); i.e., the relative permittivity $\varepsilon/\varepsilon_0$ at 400 Hz was ≈7.6. The model curve was obtained from formula (11) with $I_0 = 1$ A, $r = 8$ Ω, $\nu = 0.35$, and $\tau_0 = 30$ μs, so that the dispersion relation is $\Delta \approx 5000$ pF. The geometric factor D from (11) can be estimated from the capacitance value at 400 Hz: $D = C/\varepsilon_0 = 1000$ [pF]/$\varepsilon_0 \approx 113$ m. The difference between the relative permittivities at low and high frequencies is $\varepsilon_s - \varepsilon_\infty = 5000/113 \approx 44$, and formula (10) finally yields $\varepsilon_\infty \approx 7.4$ and $\varepsilon_s \approx 51.4$. This result agrees well with the data presented in [Pelton *et al.*, 1983].

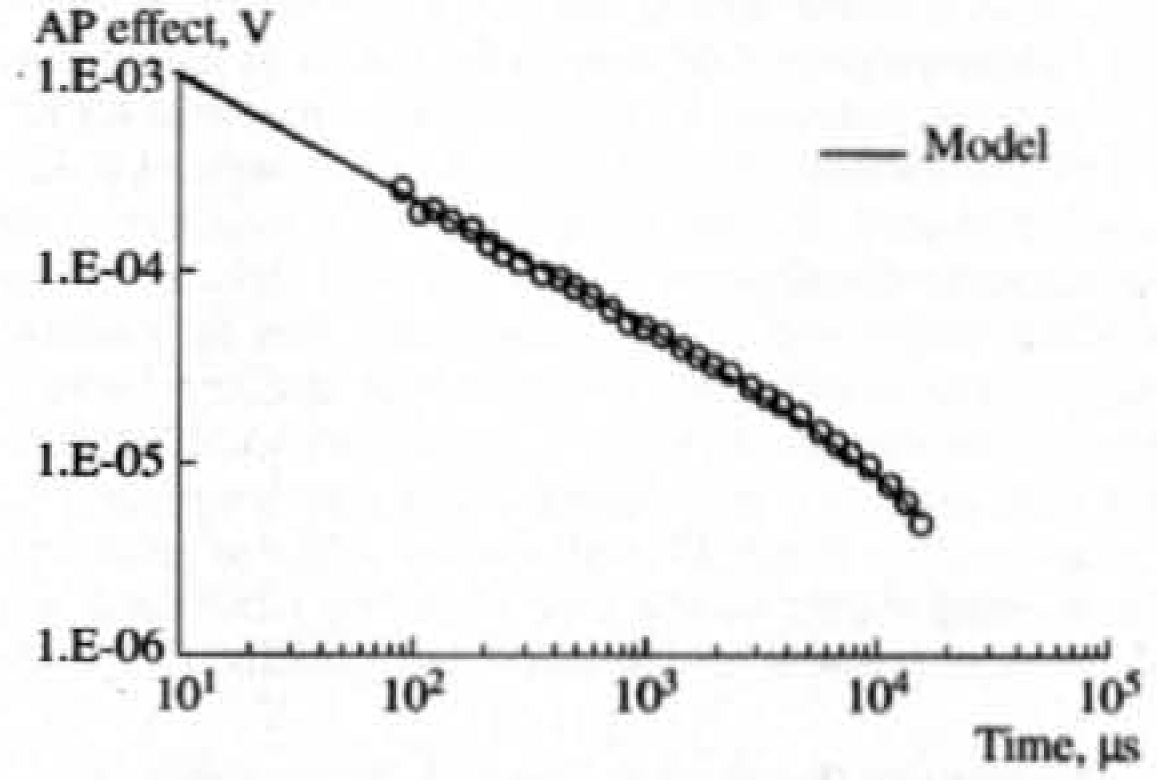

Fig. 4. Normalized characteristic of the AP effect in a 50 × 50-m antenna obtained in humid clay (transient field induction processes are removed).

In the above experiments, we placed antennas in polarizing media intentionally in order to enhance the effect studied and obtain more accurate estimates of the dispersion parameters. In practice, inductive sounding antennas are located above the medium studied, which undoubtedly weakens the AP effect. However, a fairly intense AP effect significantly distorting the TEM results at later stages and limiting the investigation depth is occasionally observed even in elevated antennas.

All of the above calculations and estimates were made for a receiving–transmitting antenna. One might suppose that the AP effect will be negligible if two separate antennas are used, one for the field transmission and another for its reception. However, this is not true.

Figure 5 plots two transient responses that were obtained from sounding experiments using a transmitting 100 × 100-m antenna in the combined variant and with a 1 × 1-m pickup of an effective area of 10^4 m^2 placed at the antenna center (the plots were kindly afforded by A. Zakharkin (Novosibirsk)). The AP effects with similar amplitudes at later stages are evident in both cases.

It is physically clear that the displacement currents flowing through the capacitors C_0 (Fig. 2) actually flow through the surrounding medium, although this does not follow directly from the formulas obtained for lines with distributed parameters. It is the polarizing medium that gives rise to the AP effect, while the antenna wires serve solely as conductors for these currents (like electrodes or capacitor plates). Note that, even if the antenna–medium system possesses an axial symmetry

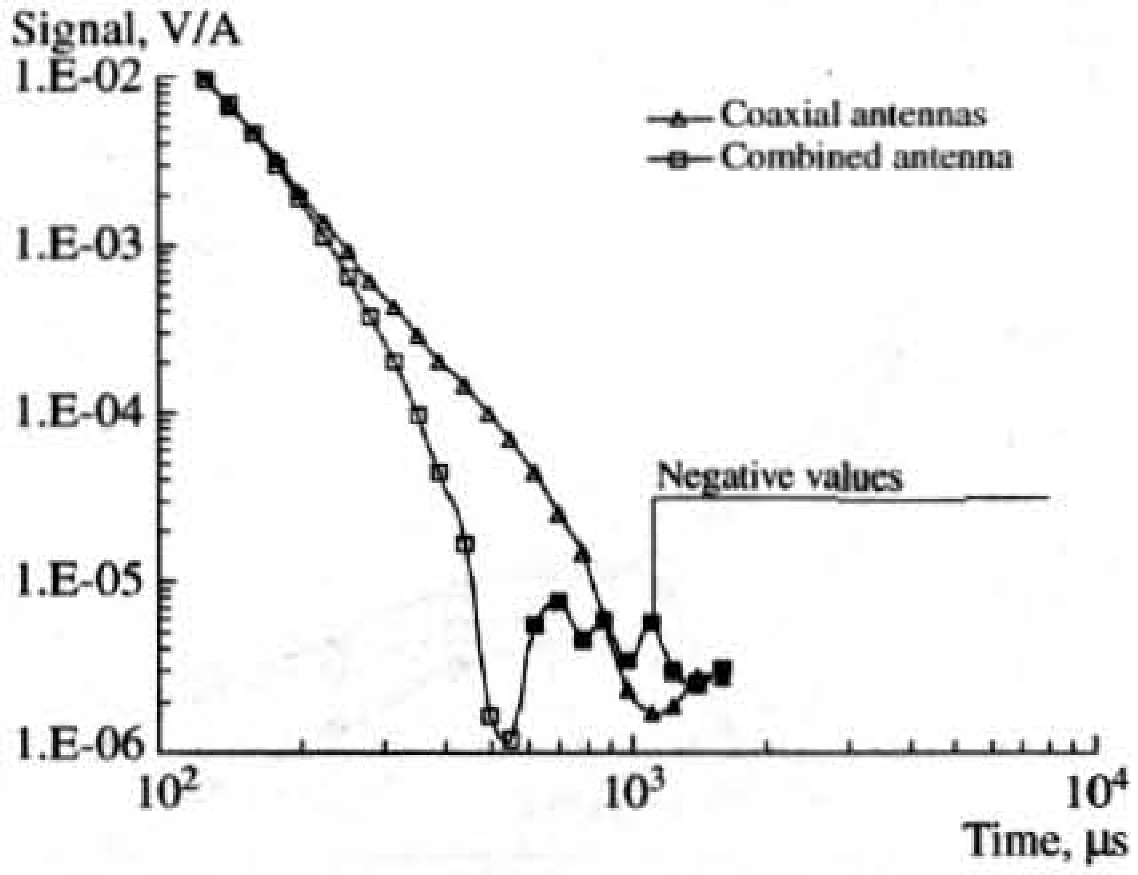

Fig. 5. Transient field responses obtained by using a 100 × 100-m antenna in the combined variant and with a pickup of an equivalent area of 10^4 m^2 placed at the center of the antenna.

(a circular antenna of a perimeter m and, for example, a homogeneous medium), the current flowing through a wire with a distributed resistance will produce an electric field asymmetric relative to the center of the circuit. The electric potential $U(x)$ between the negative terminal of the antenna ($x = 0$) and a wire element at a distance x (along the perimeter) is $U(x) = U_0x/m$. The asymmetric distribution of the potential induces in the medium radial and vertical components of the electric field (whereas only one nonvanishing angular component of the electric field E_φ is present in ideal "mathematical" circuits with a specific (per unit length) resistance equal to zero). The AP effect is due to precisely these components of the electric field, which are not taken into account in the pertinent geoelectric problems.

It is evident that the AP effect can be recorded at any point of the medium, rather than by the receiving–transmitting antenna alone; this is supported both experimentally (Fig. 5) and by numerous other results obtained in various regions of the world with various antenna configurations [Bishop and Reid, 2003]. One might suppose that field excitement by a long grounded line will also give rise to the AP effect, but this hypothesis requires a special investigation.

CONCLUSIONS

Distributed capacitance and resistance, which always exist in real arrays employed in studies of geological media with frequency-dependent permittivity, produce the antenna polarization (AP) effect. This effect arises at later stages of the field buildup and is recorded as a slow decaying process $\sim 1/t^{(0.3-0.7)}$ opposite in phase to the induction transient responses.

The AP effect depends on the dispersion parameters of the medium studied and, with a fixed current, is proportional to the squared resistance of the antenna wires (the induction processes are independent of the wire resistance).

The distributed resistance of antenna circuits produces asymmetric electric fields (with radial and vertical components) even in axially symmetric antenna–medium systems. The AP effect is recorded in both combined (receiving–transmitting) and separated antennas.

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