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Transient electric field response to a uniform, magnetically viscous earth excited by a grounded line source

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Abstract

A new method is suggested for calculation of transient electric field response to conducting magnetically viscous earth excited by a grounded line source. Calculation algorithms are implemented in the computer program *FwLL_MV*. Using a uniform, conducting magnetically viscous half-space as an earth model, we have shown that magnetic relaxation affects the TEM response of equatorial and in-line arrays. As in the case of loop arrays, apparent resistivity steadily decreases with time. The higher the half-space resistivity and the shorter the offset, the earlier the voltage and the apparent resistivity begin to decrease as $1/t$. Magnetic relaxation and decay of eddy currents are independent processes within the range of resistivities typical of rocks.

Keywords: grounded line; equatorial array; transient response; magnetic viscosity; superparamagnetism; uniform earth

Introduction

Magnetic viscosity, or a magnetic after-effect, is a property of ferrimagnetic materials to respond with a lag to the applied external field because of magnetic relaxation. The lag in their magnetization, magnetic permeability, and other changes may range from fractions of a second to tens of thousand years (Trukhin, 1973). The magnetic after-effect shows up in almost all ferrimagnetics, including rocks where it results from magnetic relaxation of single-domain grains in ferrimagnetic minerals which vary in grain sizes from fractions to hundreds of μm (Bolshakov, 1996). Relaxation times of induced magnetization in ultrafine superparamagnetic (SPM) particles of ferromagnetic minerals are from $\approx 10^{-9}$ to 10^2 s or more (Dormann et al., 1997).

The relaxation times of SPM particles are commensurate with measurement time gate of modern TEM systems, and magnetic viscosity thus affects transient responses (Kozhevnikov et al., 2012).

The known examples of magnetic viscosity effects on induction data refer to the cases of inductive excitation and sensing with ungrounded transmitter and receiver loops (Buselli, 1982; Colani and Aitken, 1966; Kozhevnikov and Snopkov, 1990, 1995; Kozhevnikov et al., 2012; Pasion et al., 2002; Stognii et al., 2010; Thiesson et al., 2007). Correspondingly, only loop arrays are considered in publications dealing with the theory of magnetic viscosity effects in induction resistivity data, as well as with respective simulations (Kozhevnikov and Antonov, 2008, 2009, 2011; Lee, 1984a,b).

Magnetic viscosity effects in data acquired with grounded transmitter and receiver lines have never been reported so far but they can be expected to exist, proceeding from the following considerations. Mutual inductance between two grounded lines depends on frequency (ω), conductivity (σ), and magnetic permeability (μ) of the earth (Mikhailov et al., 1979; Sunde, 1949), and this dependence should appear in frequency- and time-domain data because the permeability in magnetically viscous media is frequency-dependent.

Both transmitter and receiver in loop-based TEM systems can be presented as a combination of horizontal grounded lines in calculations of their transient responses. Inasmuch as loop response is sensitive to magnetic viscosity of the underlying earth (Kozhevnikov and Antonov, 2008), it is reasonable to assume the same sensitivity in grounded lines treated as loop components.

Grounded lines are currently used in induced polarization (IP) surveys. IP-affected responses commonly decay more

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slowly than the induction ones, and magnetic viscosity may remain obscured by slowly decaying IP processes. However, this does not mean it is insignificant: when undetected and not accounted for, magnetic viscosity may make latent noise and interfere with IP respose.

Thus, it is important to check whether magnetic viscosity affects grounded-line transient responses, and to reveal the manifestation and estimate the magnitude of this effect if it does exist. It is also useful to investigate the behavior of magnetic viscosity as a function of resistivity and system geometry by calculating the responses of a magnetically viscous earth recorded by grounded lines.

As far as we know, such responses have never been in focus before. Therefore, it is reasonable to begin with a simple fundamental model—a uniform conductive magnetically viscous earth, the same one that we used previously when studying how magnetic viscosity-affected loop response depends on earth's properties and system configuration and size (Kozhevnikov and Antonov, 2008).

Below we report and discuss modeling results for an equatorial array laid on a uniform conductive and magnetically viscous earth.

Magnetic relaxation and its relation with induction transients

As we mentioned, magnetic viscosity effects in induction resistivity data most often result from magnetic relaxation of ultrafine superparamagnetic grains in rocks. In this case, time-dependent magnetic susceptibility $\kappa(t)$ is (Kozhevnikov and Antonov, 2008, 2009):

$$\kappa(t) = \frac{\kappa_0}{\ln(\tau_2/\tau_1)}(B + \ln t), \tag{1}$$

where κ_0 is the static susceptibility; τ_1, τ_2 are the lower and upper bounds of the magnetic relaxation time; B is constant; t is the time after stepwise change of the primary magnetic field, which is most often within the gate $\tau_1 \ll t \ll \tau_2$.

In the frequency domain, the susceptibility $\kappa(\omega)$ is (Lee, 1984a,b)

$$\kappa(\omega) = \kappa_0\left[1 - \frac{1}{\ln(\tau_2/\tau_1)} \cdot \ln\frac{(1+i\omega\tau_2)}{(1+i\omega\tau_1)}\right], \tag{2}$$

where $i = \sqrt{-1}$ and ω is the angular frequency, s^{-1}. The frequency ω used in the practice of magnetic susceptibility measurements commonly fits the range $1/\tau_1 \ll \omega \ll 1/\tau_2$.

There are two ways to calculate induction transients affected by magnetic viscosity (Kozhevnikov and Antonov, 2008). One way is based on relationship between the magnetic flux through the receiver loop produced by the magnetization of the earth and the $\kappa(x, y, z, t)$ distribution.

After the turn-off of the transmitter current I_0, magnetic relaxation induces voltage in the receiver loop lying on a magnetically viscous earth (Kozhevnikov and Antonov, 2008):

$$e(t) = I_0 M_0 \frac{d\kappa_a}{dt},$$

where M_0 is the static mutual inductance between the transmitter and receiver loops on nonmagnetic ground; κ_a is the time-dependent apparent (effective) magnetic susceptibility controlled by the spatial distribution of $\kappa(t)$ and system geometry. $M_0 = \Phi/I_0$, where Φ is the magnetic flux through the receiver loop. M_0 equals the loop self-inductance L_0 in coincident-loop or single-loop configurations.

The calculations become simpler with analytical equations for M_0 and $\kappa_a(t)$ that exist for symmetrical (central-loop and/or coincident-loop) systems on the surface of a uniform or layered magnetic earth (Kozhevnikov and Antonov, 2008, 2009, 2011). Specifically, for a uniform earth, $\kappa_a(t) = \kappa(t)/2$, where $\kappa(t)$ is found by (1). This way is not rigorous or universal because it neglects the interplay between eddy currents and magnetic relaxation. However, as shown by previous calculations, the processes of eddy current decay and magnetic relaxation are independent, which allows finding the total transient using the principle of superposition (Kozhevnikov and Antonov, 2008, 2009).

Otherwise, induction responses are first calculated in the frequency domain, with regard to frequency dependence of magnetic permeability and then converted to the time domain (Kozhevnikov and Antonov, 2008). This is a general approach as it takes into account the eddy current-magnetic relaxation interplay.

Earlier we used both approaches to calculate transient responses of a layered magnetically viscous earth acquired by loop arrays. The earth parameters included the resistivity ρ, the static susceptibility κ_0, as well as the largest (τ_1) and smallest (τ_2) relaxation times.

However, the first approach is inapplicable to calculate the TEM response measured with grounded line arrays, as no analytical equations exist for M_0 and κ_a; thus, only the other way can be used. Unlike ungrounded loops, grounded lines have both inductive and galvanic coupling with the earth. Therefore, calculations of this responses is more challenging than in the case of ungrounded loops. The algorithm and simulation code have been designed by E. Antonov.

Transient electric field of a horizontal electrical dipole placed on a conducting magnetically viscous earth

Let a dipole electrical source lie on a conducting magnetic earth with the conductivity σ and the magnetic permeability $\mu = \bar{\mu}\mu_0$, where $\mu_0 = 4\pi \times 10^{-7}$ H/m is the air magnetic permeability and $\bar{\mu} = 1 + \kappa(\omega)$ is complex and frequency-dependent. The dipole has the moment I_x along the positive direction of the x axis and is located at the center of the Cartesian coordinates xyz (z axis directed downward; the earth-air interface at the plane $z = 0$) coinciding with the center of polar coordinates in the plane xOy (Fig. 1). The horizontal components of the transient electric field at an arbitrary point (r, φ)

on the earth surface are found using separation of variables (also known as the Fourier method), in the frequency domain with subsequent transformation to the time domain by integration of the harmonic electric field along the real-value frequency axis (Tabarovsky and Sokolov, 1982):

$$E(r, z, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} E(r, z, \omega) \frac{e^{-i\omega t}}{-i\omega} d\omega.$$

The horizontal components of the electric dipole field in the frequency domain are found as (Tabarovsky, 1975):

$$^{I_x}E_x(r, z, z_0, \omega) = \frac{I}{4\pi\sigma} \int_0^{\infty} \frac{\partial f^E}{\partial z \partial z_0} [J_0(\lambda r) - \cos 2\varphi J_2(\lambda r)] \lambda d\lambda$$

$$+ \frac{I\omega\mu I}{4\pi} \int_0^{\infty} f^H [J_0(\lambda r) + \cos 2\varphi J_2(\lambda r)] \lambda d\lambda, \quad (3)$$

$$^{I_y}E_y(r, z, z_0, \omega) = -\frac{I \sin 2\varphi}{4\pi\sigma} \int_0^{\infty} \frac{\partial f^E}{\partial z \partial z_0} J_2(\lambda r) \lambda d\lambda$$

$$+ \frac{i\omega\mu I \sin 2\varphi}{4\pi} \int_0^{\infty} f^H J_2(\lambda r) \lambda d\lambda, \quad (4)$$

$$\left. \frac{\partial f^E}{\partial z \partial z_0} \right|_{z = z_0 = 0} = -p, \quad (5)$$

$$\left. f^H \right|_{z = z_0 = 0} = \frac{\mu}{\mu\lambda + \mu_0 p} = \frac{\bar{\mu}}{\bar{\mu}\lambda + p}, \quad (6)$$

where $p = \sqrt{\lambda^2 + k^2}$, $k^2 = -i\omega\mu\sigma$; λ is the spatial frequency; $\bar{\mu} = 1 + \kappa$ is the relative magnetic permeability; κ is the earth's magnetic susceptibility; z_0 and z are the vertical coordinates of the source and receiver, respectively. The variables f^E, f^H refer to the so-called basic functions of the electric- or magnetic-type solutions to the forward problem for a horizontally-layered earth. These functions depend on the earth properties, spatial frequency, and the source and receiver vertical coordinates but independent of the source properties and field components. The recursive algorithm for calculating fundamental functions in the layered problem was described in detail by Tabarovsky (1979). Obviously, for a nonmagnetic earth, $\bar{\mu} = 1$, $\kappa = 0$ and, correspondingly, the magnetic mode of the layered function is

$$\left. f^H \right|_{z = z_0 = 0} = \frac{1}{\lambda + p}. \quad (7)$$

After small transformations, with regard to known recurrent equations (Abramowitz and Stegun, 1972)

$$J_2(\lambda r) = \frac{2}{\lambda r} J_1(\lambda r) - J_0(\lambda r), \quad (8)$$

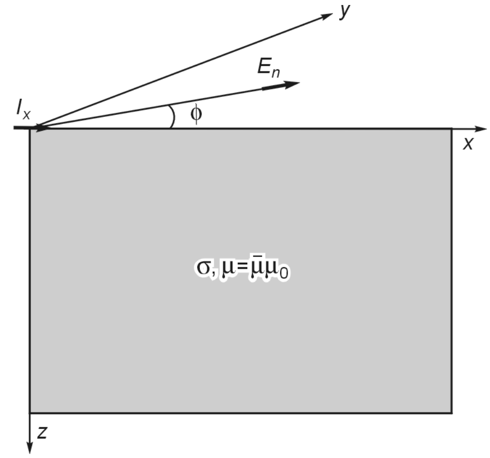

Fig. 1. Horizontal electric dipole on the earth's surface.

the equations for the electric field components (3) and (4) can be written as a sum of integrals $^{I_x}E_\alpha = \sum_{i=1}^{4} A_i^\alpha I_i$, $\alpha = (x, y)$, where

$$I_1 = \int_0^{\infty} p J_0(\lambda r) \lambda d\lambda, \quad (9)$$

$$I_2 = \int_0^{\infty} p J_1(\lambda r) d\lambda, \quad (10)$$

$$I_3 = \int_0^{\infty} \frac{\bar{\mu}}{\bar{\mu}\lambda + p} J_0(\lambda r) \lambda d\lambda, \quad (11)$$

$$I_4 = \int_0^{\infty} \frac{\bar{\mu}}{\bar{\mu}\lambda + p} J_1(\lambda r) d\lambda, \quad (12)$$

$$A_1^x = -\frac{I(1 + \cos 2\varphi)}{4\pi\sigma}, \quad A_2^x = \frac{I \cos 2\varphi}{2\pi\sigma r},$$
$$A_3^x = \frac{Ii\omega\mu(1 - \cos 2\varphi)}{4\pi}, \quad A_4^x = \frac{Ii\omega\mu \cos 2\varphi}{2\pi r}, \quad (13)$$

$$A_1^y = -\frac{I \sin 2\varphi}{4\pi\sigma}, \quad A_2^y = \frac{I \sin 2\varphi}{2\pi\sigma r},$$
$$A_3^y = -\frac{Ii\omega\mu \sin 2\varphi}{4\pi}, \quad A_4^y = \frac{Ii\omega\mu \sin 2\varphi}{2\pi r} \quad (14)$$

Integrals (9–12) for a conducting nonmagnetic earth ($\bar{\mu} = 1$, $\kappa = 0$) are reduced to table integrals, while the electric field components $^{I_x}E_x$ and $^{I_x}E_y$ can be expressed analytically (Spies and Frischknecht, 1991; Veshev, 1965):

$$^{I_x}E_x^{An} = \frac{I}{2\pi\sigma r^3} \left[3\cos^2\varphi - 2 + (1 + kr) e^{-kr} \right], \quad (15)$$

$$ {}^{I_x}E_y^{An} = \frac{3\cos\varphi\sin\varphi I}{2\pi\sigma r^3}. \quad (16) $$

The equations are valid to account for induced polarization. In this case, it is enough to use the respective presentation for conductivity, for instance, with the Cole–Cole model (Lee, 1981).

However, in the case of a magnetic earth, integrals (11) and (12) cannot be reduced to the table integrals, and require numerical integration. For real magnetic permeability, the solutions for transients can be obtained with (11), (12) by changing the sequence of transformations with respect to the angular (ω) and spatial (λ) frequencies (Ignetik et al., 1985; Wait, 1982), but numerical methods are required anyway.

Equations (3) and (4) can be presented as a sum of analytical equations (15) and (16) found for complex magnetic permeability plus some correction not included into these equations. Such a correction is obviously necessary to calculate the source-orthogonal component E_y. Equation (16) for a nonpolarizable and/or nonmagnetic earth is independent of frequency and, correspondingly, does not contribute to transient responses associated with the turn-off of the primary field. Thus, the correction is applied to account for the earth magnetic properties in the component E_y. To find this correction, the part of the fundamental function associated with the magnetic properties of the earth has to be separated from integrands of (11), (12). With regard to (6) and (7), the basic function for the correction is given by

$$ \frac{\overline{\mu}}{\overline{\mu}\lambda + p} - \frac{1}{\lambda + p} = \frac{p\kappa}{(\lambda + p + \lambda\kappa)(\lambda + p)}. $$

The integrals in the equation for calculating the correction are

$$ I_3^{MV} = \int_0^\infty \frac{p\kappa J_0(\lambda r)\lambda d\lambda}{(\lambda + p + \lambda\kappa)(\lambda + p)}, \quad (17) $$

$$ I_4^{MV} = \int_0^\infty \frac{p\kappa J_1(\lambda r)d\lambda}{(\lambda + p + \lambda\kappa)(\lambda + p)}. \quad (18) $$

Finally, equations (9), (10) for the electric field components in a magnetic earth become

$$ {}^{I_x}E_x = {}^{I_x}E_x^{An} + A_3^x I_3^{MV} + A_4^x I_4^{MV}, $$

$$ {}^{I_x}E_y = {}^{I_x}E_y^{An} + A_4^y I_3^{MV} + A_4^y I_4^{MV}. $$

The integrals I_3^{MV} and I_4^{MV}(17), (18) are found numerically. In ground TEM surveys, both transmitter and receiver lie on a horizontal plane. In this case, the integrals of the form (17), (18) converge poorly and are calculated by deformation of the integration path in a complex plane. For forward resistivity and electromagnetic induction problems, the method was described in several publications (Mogilatov and Potapov, 2014; Wait, 1982; Zaborovsky, 1963). Using the equation for the Bessel functions as a sum of the first and second-order Hankel functions (Abramowitz and Stegun, 1972)

$$ J_\nu(z) = \frac{1}{2}\left[H_\nu^{(1)}(z) + H_\nu^{(2)}(z)\right], $$

and the equations

$$ K_\nu(z) = \frac{i\pi}{2} e^{i\pi\nu/2} H_\nu^{(1)}(iz) = -\frac{i\pi}{2} e^{-i\pi\nu/2} H_\nu^{(2)}(-iz), $$

equations (17), (18) can be brought to exponentially decaying modified Bessel functions $K_0(z)$ and $K_1(z)$. We apply integration in the complex plane $z = \lambda_x + i\lambda_y$ along $\lambda_c = \lambda_x(1 + it)$ and $\overline{\lambda}_c = \lambda_x(1 - it)$, where $t = \tan\alpha$, instead of the integration along the real axis in (17), (18); the slope α is chosen such that $\mathrm{Re}(p) \le 0$ (Tabarovsky, 1975).

As a result, equations (17) and (18) become

$$ I_3^{MV} = \frac{i}{\pi}\left[-\int_0^\infty \frac{K_0(-i\lambda_c r)p_c\kappa\lambda_c d\lambda_c}{(\lambda_c + p_c + \lambda_c\kappa)(\lambda_c + p_c)} + \int_0^\infty \frac{K_0(i\overline{\lambda}_c r)p\kappa\overline{\lambda}_c d\overline{\lambda}_c}{(\overline{\lambda}_c + \overline{p}_c + \overline{\lambda}_c\kappa)(\overline{\lambda}_c + \overline{p}_c)}\right], \quad (19) $$

$$ I_4^{MV} = -\frac{1}{\pi}\left[\int_0^\infty \frac{K_1(-i\lambda_c r)p_c\kappa d\lambda_c}{(\lambda_c + p_c + \lambda_c\kappa)(\lambda_c + p_c)} + \int_0^\infty \frac{K_1(i\overline{\lambda}_c r)\overline{p}_c\kappa d\overline{\lambda}_c}{(\overline{\lambda}_c + \overline{p}_c + \overline{\lambda}_c\kappa)(\overline{\lambda}_c + \overline{p}_c)}\right], \quad (20) $$

where $\lambda_c = \lambda_x(1 + it)$, $\overline{\lambda}_c = \lambda_x(1 - it)$, $t = \tan\alpha$, $i = \sqrt{-1}$, $p_c = \sqrt{\lambda_c^2 + k^2}$, $\overline{p}_c = \sqrt{\overline{\lambda}_c^2 + k^2}$.

Figure 2 shows the resulting transients in the time domain for an equatorial system on a magnetically viscous earth. The transmitter and receiver lines (*AB* and *MN*) are 100 m and 20 m long, respectively, and are spaced at $r = 10$ m. The resistivity is Ohm·m, SI units, $\tau_1 = 10^{-6}$ s, $\tau_2 = 10^6$ s. The panels *a* and *b* of Fig. 2 show, respectively, the current-normalized transient ΔU_x and its components ΔU_{An} and ΔU_{MV} found by (15) plus the correction calculated using (17) and (18) equations (Fig. 2*a*) and the $\Delta U_{MV}/\Delta U_{An}$ curve (Fig. 2*b*). The correction not included into the analytical equations (15), (16) is large and may lead to a significant error in field calculations if neglected.

Model and array parameters

As in the previous studó of loop transient responses (Kozhevnikov and Antonov, 2008), the calculations discussed in this paper were made assuming $\tau_1 = 10^{-6}$ s, $\tau_2 = 10^6$ s and the static magnetic susceptibility $\kappa_0 = 10^{-2}$ SI units, which is of the same order of magnitude as κ_0 obtained by inversion of induction transients for tuffs and traps in the Malaya Botuobiya area in Western Yakutia (Stognii et al., 2010) and for the Vitim Plateau basalts in Transbaikalia (Antonov et al., 2011; Kozhevnikov and Antonov, 2012).

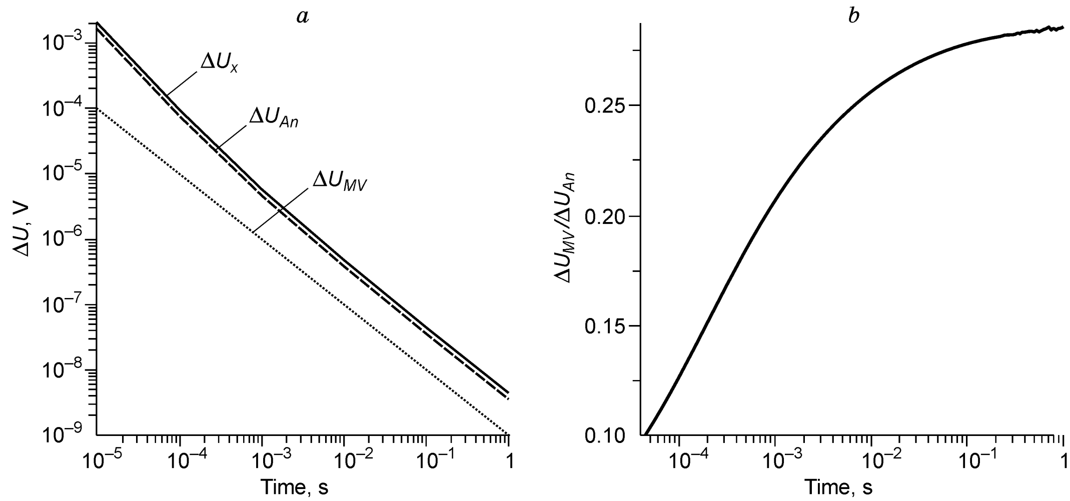

Fig. 2. Calculated transient voltage U_x and its components (ΔU_{An}, ΔU_{MV}) for an equatorial array.

The calculations were done for equatorial and in-line arrays, with a 100 m long transmitter line (*AB*) and a 20 m long receiver line (*MN*), their lengths corresponding to the size of loop systems that are often reported as being sensitive to magnetic viscosity effects. Such arrays are commonly used in IP studies. The magnetic viscosity effects turned out to be the same in data of both arrays, and the considerations below are thus restricted to the equatorial configuration.

The transients were calculated in the time range from 10 μs to 1 s corresponding to the characteristic times of induction (TEM) and electrochemical (IP) responses.

Results

The reported numerical experiment aimed at investigating time-domain magnetic viscosity respose as a function of offset and earth resistivity.

In order to study the interplay of magnetic relaxation and eddy current decay as a function of resistivity, transients were calculated for an offset of r = 10 m and a resistivity from 1 to 10^6 Ohm·m. With such a short offset, the equatorial array is similar to a symmetrical Schlumberger array often used in the survey practice.

Current-normalized voltage decay curves $e(t)/I$ in Fig. 3 represent responses of a nonmagnetic (*a*) and a magnetically viscous (*b*) earth. In the case of a nonmagnetic earth (Fig. 3*a*), after some time, which is shorter at higher resistivity, the voltage decay is inversely proportional to $t^{3/2}$: $e(t)/I \propto 1/t^{-3/2}$. The curves in panels *a* and *b* coincide at early times, i.e., the magnetic viscosity effects remain irresolvable against the eddy current contribution.

At late times, voltage decay associated with magnetic relaxation is slower; the time when the effect becomes evident is inversely proportional to resistivity. With time, voltage decays ever more slowly: $e(t)/I \propto 1/t$. The same decay is observed in loop responses and is diagnostic of magnetic viscosity (Buselli, 1982; Colani and Aitken, 1966; Kozhevnikov and Antonov, 2008).

For late times, apparent resistivity (ρ_a) curves (Fig. 4) are calculated as (Spies and Frischknecht, 1991)

$$\rho_a = \frac{L_{AB}^2 \mu_0^3}{144\pi^3 t^3}\left[\frac{e(t)}{L_{MN} I}\right]^{-2},$$

where t is the time, s; L_{AB} and L_{MN} are the lengths of the transmitter and receiver lines, respectively, m; I is the transmitter current, *A*; $e(t)$ is the voltage induced in the receiver line, *V*.

The magnetic viscosity effects are more prominent in ρ_τ curves than in those of voltage decay (compare Fig. 4*a* and Fig. 4*b*). The ρ_τ values become equal to the resistivity of nonmagnetic earth at some late times (Fig. 4*a*). The effect of magnetic relaxation appears as progressive ρ_τ decrease till the asymptote where the apparent resistivity decreases as $1/t$ (Fig. 4*b*); the higher the resistivity the earlier the ρ_τ decrease becomes evident.

To optimize TEM surveys in potentially magnetically viscous areas, it is useful to know how magnetic relaxation effects in data depend on the system geometry and size. The influence of offset (1, 10, 10^2, and 10^3 m) on apparent resistivity (ρ_a) curves is shown in Fig. 5 for ρ =10, 10^2, and 10^3 Ohm·m and $\kappa_0 = 10^{-2}$ SI units.

The left branches of the ρ_a curves are above the horizontal lines at $\rho_a = \rho$. The ρ_a overshoot with respect to ρ is higher at lower resistivities, longer offsets, and shorter delay times. The reason is that the apparent resistivity calculations were made using late times formula (Spies and Frischknecht, 1991). For nonmagnetic earth, ever decreasing ρ_a vs. ρ difference would be observed with increasing t, in the same way as in Fig. 5*a*. Magnetic relaxation causes progressive ρ_a decrease with t; the effect is less prominent at lower resistivities and longer offsets, but it is still notable even at $r = 10^3$ m at 10^2 and 10^3 Ohm·m; at ρ = 10 Ohm·m, magnetic relaxation becomes evident at $r \le 100$ m.

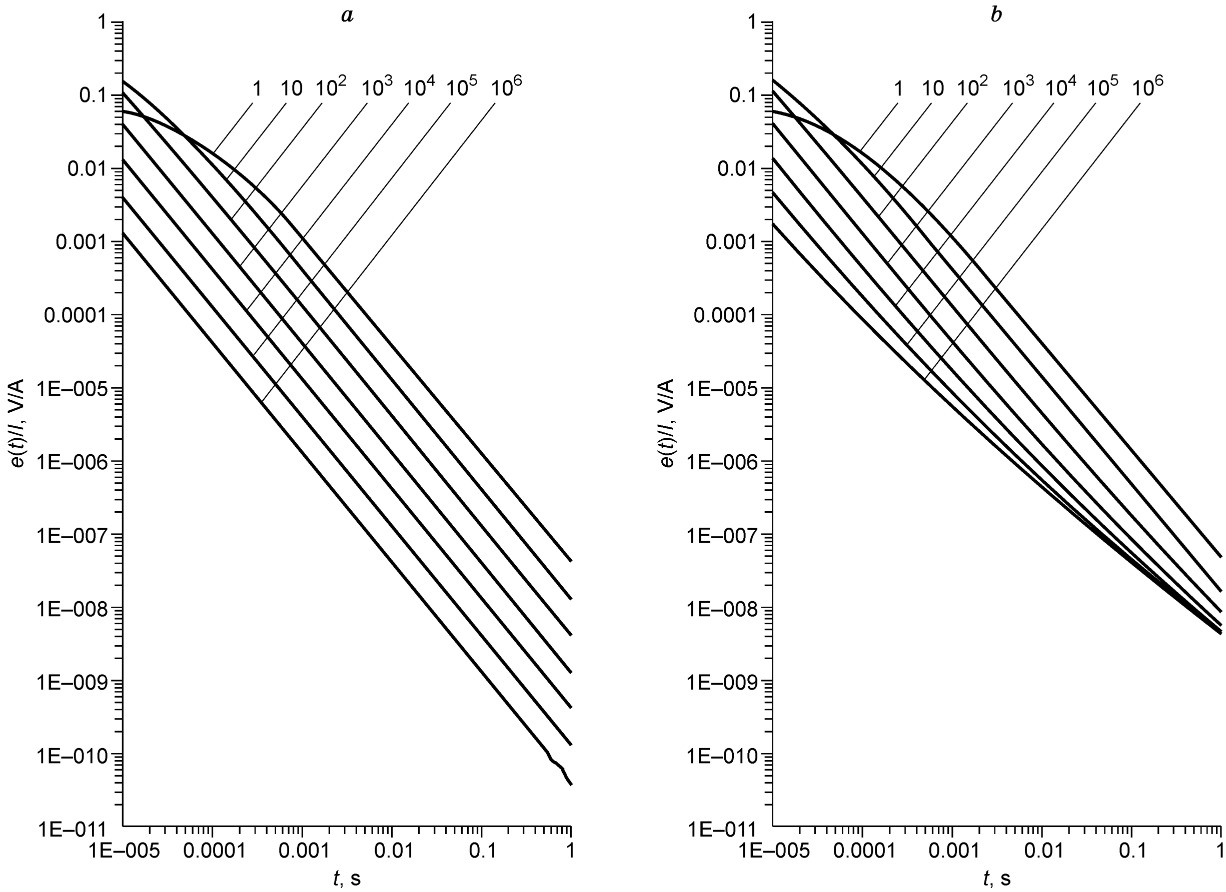

Fig. 3. Transient voltage responses: *a*, uniform conducting earth; *b*, uniform conducting and magnetically viscous earth ($\kappa_0 = 10^{-2}$ SI units). Equatorial array: AB = 100 m, MN = 20 m, r = 10 m. Numerals at curves are resistivity in Ohm·m.

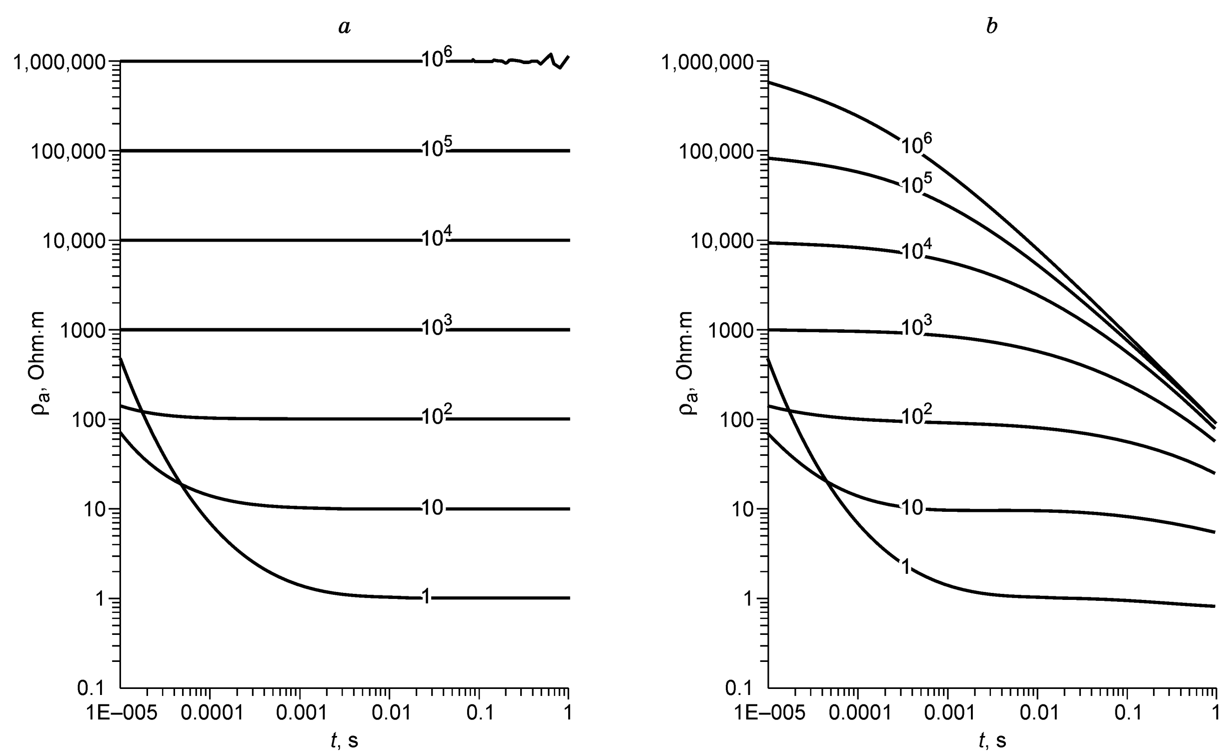

Fig. 4. Apparent resistivity (ρ_a) curves: *a*, uniform conducting earth; *b*, uniform conducting and magnetically viscous earth ($\kappa_0 = 10^{-2}$ SI units). Equatorial array: AB = 100 m, MN = 20 m, r = 10 m. Numerals at curves are resistivity in Ohm·m.

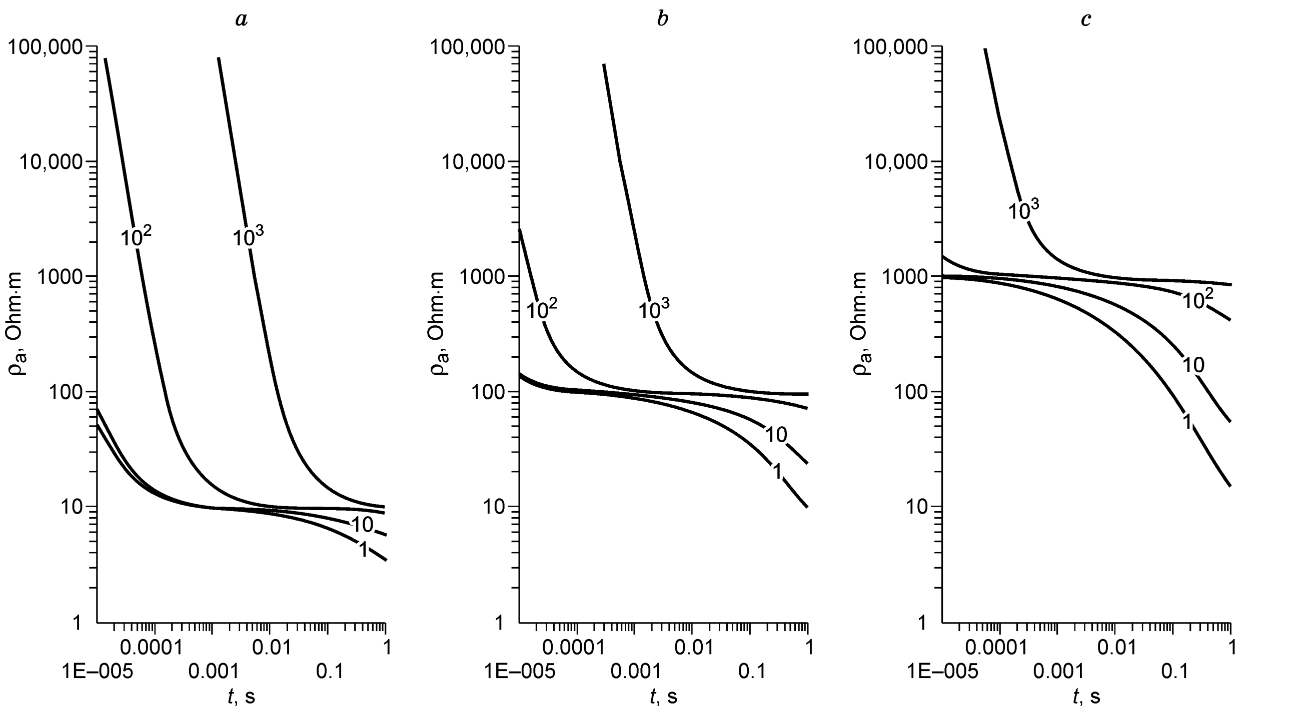

Fig. 5. Apparent resistivity (ρ_a) curves for an equatorial array on a magnetically viscous earth ($\kappa_0 = 10^{-2}$ SI units), with a resistivity of 10 (*a*), 10^2 (*b*), and 10^3 (*c*) Ohm·m. Numerals at curves are offset (*r*) in m.

In our previous studies of ungrounded loop transient responses of a magnetically viscous earth (Kozhevnikov and Antonov, 2008, 2009), magnetic relaxation and eddy current decay were shown to be independent.

The calculations of the *AB–MN* equatorial array transients (Fig. 6) began with the voltage decay $e_1(t)/I$ in the receiver line for a conducting (ρ = 10, 10^2, and 10^3 Ohm·m) nonmagnetic (κ_0 = 0) earth and then proceeded to the case of κ_0 = 0.01 and $\rho = 10^6$ Ohm·m. Eddy currents decay very rapidly at these resistivities, and voltage in the receiver line ($e_2(t)/I$) is induced mostly by magnetic relaxation even at early times.

Then we calculated the total voltage $e_\Sigma(t)/I = e_1(t)/I + e_2(t)/I$ (see the curves in Fig. 6, along with the $e(t)/I$ curves found with regard to the eddy current-magnetic relaxation interplay for κ_0 = 0.01 SI units, ρ = 10, 10^2, and 10^3 Ohm·m). The curves $e_\Sigma(t)/I$ and $e(t)/I$ coincide, this meaning that the two processes are independent, as in the case of loop arrays. Therefore, the superposition principle is valid for calculating transient responses of a magnetically viscous earth in the case of grounded lines as well.

Discussion

Forward modeling shows that grounded-line array response is affected by magnetic viscosity in the same way as those of loop arrays. In both cases, voltage induced by magnetic relaxation and apparent resistivity decay inversely proportional to time ($\propto 1/t$).

The physics of the effect was discussed previously for the case of loop responses (Kozhevnikov and Antonov, 2008). The transmitter primary magnetic field magnetizes the target object and the latter produces the secondary field which remains after the primary filed has been turned-off. The secondary field decays synchronously with viscous magnetization, and the decaying magnetic flux induces voltage in the receiver loop. In this case, there exist two inductively coupled closed loops

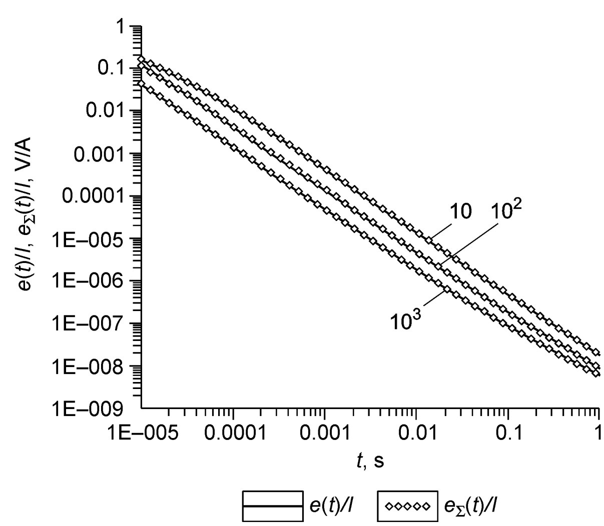

Fig. 6. TEM voltage responses for an equatorial array (*AB* = 100 m, *MN* = 20 m, *r* = 10 m), calculated by rigorous and approximate ways. The array is on uniform conducting and magnetically viscous earth ($\kappa_0 = 10^{-2}$ SI units). Numerals at curves are resistivity in Ohm·m.

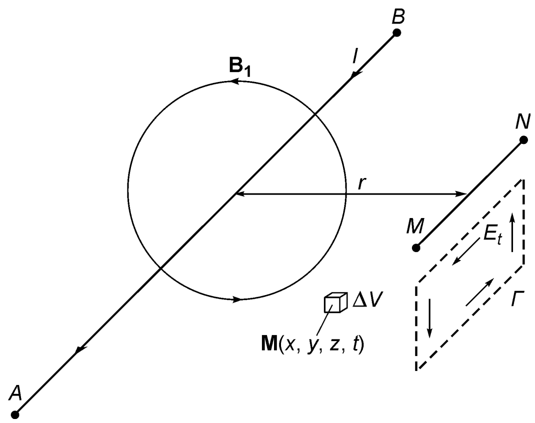

Fig. 7. Equatorial array on a uniform conducting and magnetically viscous earth.

made of insulated wire; actually, the transmitter and receiver loops make up a transformer with the properties of its core depending on objects in the vicinity of the loops and on the properties of the earth.

The case of grounded lines is more complicated. The primary magnetic field results from both currents in the transmitter line and currents flowing in the earth, and there is no wire receiver loop.

In the equatorial array (Fig. 7), the current I in the transmitter line AB enters the earth at the electrode A and turns back to the line at the electrode B (the current distribution in the earth is not shown in the figure for simplicity). Currents in the wire and in the earth produce the primary magnetic field under the action of which each elementary volume ΔV of the earth aquires the magnetization $\mathbf{M}$ (Fig. 7 shows the field $\mathbf{B}_1$ produced by current in the wire). Each elementary volume ΔV with the magnetization $\mathbf{M}$ has the magnetic moment $\Delta\mathbf{M} = \mathbf{M}\Delta V$; the secondary magnetic field $\mathbf{B}_2(t)$ is a sum of fields produced by all elementary volumes ΔV.

After the current turn-off and removal of the primary field, magnetization disappears very rapidly, unless the earth amterial is not magnetically viscous. In the case of magnetically viscous earth, magnetization and secondary magnetic field in the earth decay slowly.

Magnetic flux through the loop placed in the vertical plane below the line MN is

$$\Phi = \int_S B_{2n}(t)\, dS,$$

where S is an arbitrary surface bounded by the loop Γ and B_{2n} is the magnetic field component normal to the surface S.

According to Faraday's law, the time-dependent magnetic flux Φ induces the voltage $e(t)$ in the loop Γ:

$$e(t) = \oint_\Gamma E_l\, dl = -\frac{d\Phi}{dt},$$

where E_l is the component of vortex electric field directed along the loop; dl is an infinitesimal line element of the loop. The voltage $e(t)$ induces eddy current in the loop Γ, which flows along the ground surface and produces the potential difference between the electrodes M and N of the receiver line.

The loop Γ in Fig. 7 corresponds to one of many such loops or one of many current lines in the earth. Potential difference between the electrodes M and N is an overall effect due to all secondary currents distributed in the earth.

The actual situation is obviously more complicated than the above simplified model because the inductance between the transmitter and receiver lines depends on both magnetic permeability and resistivity of the earth.

Note in conclusion that, when studied with grounded lines, the earth should be conducting, i.e., its resistivity should be finite. As for the loop arrays, they can be used in magnetic viscosity studies even in the case of nonconductive earth.

Conclusions

A new method is suggested for calculation of transient electric field response to conducting magnetically viscous earth excited by a grounded line source. Calculation algorithms are implemented in the computer program *FwLL_MV*.

Using a uniform, conducting magnetically viscous half-space as an earth model, we have shown that magnetic relaxation affects the TEM response of equatorial and in-line arrays.

As in the case of loop arrays, apparent resistivity steadily decreases with time. The higher the half-space resistivity and the shorter the offset, the earlier the voltage and the apparent resistivity begin to decrease as $1/t$.

For typical rock resistivities, magnetic relaxation and decay of eddy currents are independent processes.

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