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ScienceDirect

Russian Geology and Geophysics 58 (2017) 855–863

RUSSIAN GEOLOGY
AND GEOPHYSICS

www.elsevier.com/locate/rgg

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

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Received 24 February 2016; accepted 6 July 2016

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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http://dx.doi.org/10.1016/j.rgg.2017.06.008

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)