Russian Geology and Geophysics © 2019, V.S. Sobolev IGM, Siberian Branch of the RAS
Vol. 60, No. 3, pp. 492–499, 2019 DOI:10.15372/RGG2019027 *Geologiya i Geofizika*

Effect of Transmitter Current Waveform on Transient Electromagnetic Responses

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Received 16 February 2018; received in revised form 29 April 2018; accepted 15 June 2018

Abstract—The theoretical studies and methodological guidelines for transient electromagnetic (TEM) surveys assume an ideal step turn-off of transmitter current. Yet, the pulse duration in the survey practice is nonzero: It depends on penetration depth and has economic or logistic limitations. The turn-off time, which cannot be too short for technical reasons, affects especially the late-time transient responses, while the transmitter waveform is more essential at early times. Therefore, forward calculations of voltage decay should take into account the real parameters of the turn-off ramp. Earlier it was suggested to use transmitter current of a special waveform to improve the resolution of TEM soundings, e.g., in the designed and successfully tested compensation method. In this study the problem is treated from a broader perspective, in terms of TE and TM polarization of the TEM field. The two components are excited by different sources and behave in different ways in responses of a two-layer earth with a resistive lower layer to transmitter current of different waveforms.

Keywords: resistivity survey, TEM soundings, transmitter waveform, TE field, TM field

INTRODUCTION

Both theoretical (Vaniyan, 1965) and methodological (Zakharkin, 1981) studies for transient electromagnetic (TEM) surveys assume that transmitter current turns off instantly (an ideal step turn-off). Yet, the actual pulse duration time in the survey practice is always nonzero: it depends on penetration depth and has economic or logistic limitations. The required energy can be achieved at the account of the amplitude of a shorter pulse. The step duration, which cannot be too short for technical reasons, affects late-time responses, while the voltage decay at early times depends more on the transmitter waveform. Therefore, forward calculations of voltage decay should take into account the real parameters of the turn-off ramp. The problem was discussed in a number of earlier publications (Sokolov et al., 1978; Zakharkin, 1981; Fitterman and Anderson, 1987; Epov et al., 1996; Liu, 1998). Previously it was suggested to use a special current waveform for improving the resolution of TEM soundings, e.g., in a designed and successfully tested compensation method (Isaev, 1983; Isaev and Trigubovich, 1983).

In this respect, the question arises whether the performance of TEM surveys can be improved by varying the current waveform. It is reasonable to view the problem in a broader perspective in terms of TE and TM polarization of the TEM field. The two components are excited by different sources and differ dramatically in waveform effects on responses of a two-layer earth with a resistive lower layer. TEM soundings which use magnetic component (TE polarization) are of limited potentiality. The TE field becomes almost independent of transmitter waveform at late times, when deep penetration is the most efficient, but depends only on the pulse area (energy). The electric component (TM field), on the contrary, preserves the waveform dependence at late times and records geoelectrical parameters of the subsurface. This analysis is the new result we report in this study.

First we discuss common problems in TEM surveys with loop and line transmitters.

EFFECT OF TURN-OFF RAMP ON EARLY-TIME VOLTAGE DECAY

Taking into account linear (or other) behavior of voltage decay in response to transmitter turn-off is a common problem in TEM data processing. Transmitter current does not stop instantly and the turn-off is actually linear rather than being an ideal step (Fig. 1). The turn-off time depends on the loop size and varies in practice from microseconds to milliseconds. This aspect has been largely discussed in the literature (Zakharkin, 1981; Liu, 1998; Fitterman, 1987; Ivanova, 2017). The problem is that express data interpretation requires tried and tested techniques for step turn-off.

Below we compare transient responses to linear and step turn-off using a model of an in-loop array (a receiver with an

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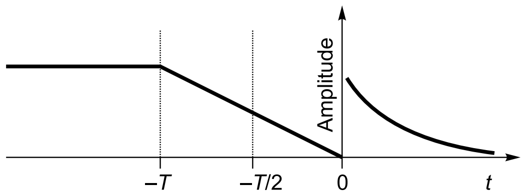

Fig. 1. Linear transmitter turn-off. t is the turn-off time.

effective area equivalent to a 100 m × 100 m loop at the center of a transmitter loop 564 m in diameter; current 100 A; dB_z/dt measured at the center) on the surface of a two-layer earth with a conducting upper layer (h = 1250 m, ρ = 10 Ohm×m) and a resistive lower layer. The voltage is due to step turn-off at $\tau = 0$, $\tau = -T/2$ and $\tau = -T$, where T is the linear turn-off time; the count is from time zero $t = 0$.

The voltage decay curves for $T = 0.5$ ms (Fig. 2*a*) for the linear and step (at $\tau=-T/2$) turn-off almost coincide. This is a known and understandable fact which results from the dB_z/dt behavior at early times and, in general, from smooth linear voltage behavior within short time intervals. One has to bear in mind, however, that substituting step for linear turn-off at a shift to $T/2$ may be incorrect for other components, at larger ramp widths, and at nonlinear distortions. See, for instance, the lack of coincidence in similar curves for a 5 ms linear ramp in Fig. 2*b*.

Of course, the most reasonable solution will be to lock the true current waveform in the field and to account for this waveform in the processing software, which has become standard nowadays.

EFFECT OF TURN-OFF RAMP ON LATE-TIME TEM RESPONSES (LOOP AND LINE TRANSMITTERS)

The asymptotic voltage decay at $t \to \infty$ in the case of ideal step turn-off is given by

$$F(t) \approx \frac{A}{t^{\alpha}}, \tag{1}$$

Table 1. Late-time exponential dependence of voltage decay

Loop, M_z	H_r	H_z	$\partial B_r/\partial t$	$\partial B_z/\partial t$
Exponent	2	3/2	3	5/2
Line, L_x	E_x	E_y	H_z	$\partial B_z/\partial t$
Exponent	3/2	3	3/2	5/2

where α is an integer or a fraction.

For any source type and field component, the exponent can be obtained formally from analytical equations of late-time voltage decay in simple models, such as a conductive earth or a condive plane in air. Obviously, it is easy to show the solution to (1) in a graphic form, by plotting the ratio

$$\alpha = \frac{\lg\left|F(t)/F(t+\Delta t)\right|}{\lg\left[(t+\Delta t)/t\right]}, \tag{2}$$

where $F(t)$ is the voltage decay; t is the time; Δt is a small time increment. Figure 3 shows the respective curves for the electric and magnetic field components induced by loop and line transmitters, for a conductive halfspace. Calculating the exponent for the electric component orthogonal to the trnasmitter line, which is zero on the surface of a conducting nonploarizable earth (E_y in our model), is a special case. We found the exponent α for a conductive halfspace under a thin layer, assuming DC transmitter current (see the summary of results in Table 1).

For a square turn-off ramp, with a width of $\Delta\tau$ (Fig. 4), the asymptotic decay at quite large t is given by (Wait, 1982):

$$^{\Delta\tau}E(t) = E_0(t+\tau) - E_0(t+\tau+\Delta\tau)$$

$$\approx \frac{A}{(t+\tau)^{\alpha}} - \frac{A}{(t+\tau+\Delta\tau)^{\alpha}}$$

$$= \frac{A}{t^{\alpha}}\left[\frac{1}{(1+\bar{\tau})^{\alpha}} - \frac{1}{(1+\bar{\tau}+\Delta\bar{\tau})^{\alpha}}\right]$$

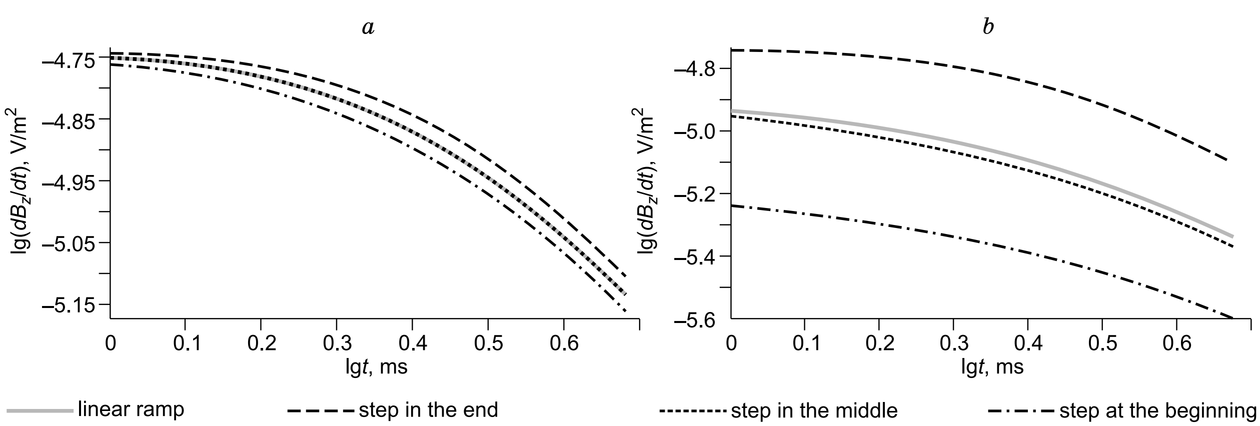

Fig. 2. TEM responses to linear turn-off. a, 0.5 ms ramp width, *b*, 5 ms ramp width. Step turn-off at the beginning, in the middle, and in the end of the ramp.

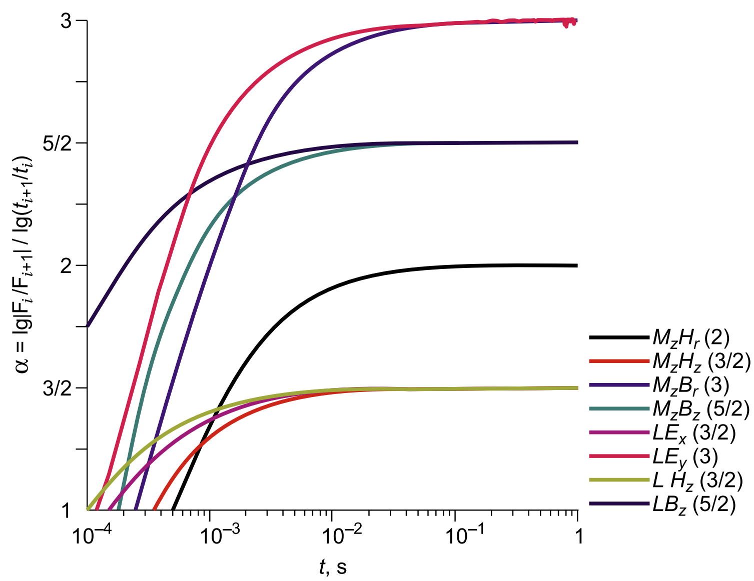

Fig. 3. Late-time exponents for the electric and magnetic field components.

$$\approx E_0(t)\left[\frac{1}{(1+\overline{\tau})^{\alpha}}-\frac{1}{(1+\overline{\tau}+\Delta\overline{\tau})^{\alpha}}\right]. \qquad (3)$$

Hereafter $E_0(t)$ is the response to an infinite DC current step, at $\overline{\tau}=\tau/t$.

The turn-off time dependence is shown in Fig. 5; solid lines in the panels *a* and *b* are for infinite width pulses; other lines are for 0.10, 0.25 and 0.50 s square pulses. The calculations were performed for $\frac{\partial B_z}{\partial t}$ for loop (Fig. 5*a*) and line (Fig. 5*b*) transmitters. Figure 5 provides spectacular illustration to equation (3) showing that the increment $\Delta\tau$ appears only at the times $t \geq \Delta\tau$ irrespective of the transmitter-receiver configuration.

With (3), it is easy to derive an equation for a square pulse of the width T:

$${}^{T}E(t)\approx E_0(t)\frac{\alpha}{t}\int_0^T\frac{d\tau}{(1+\overline{\tau})^{\alpha+1}}=E_0(t)\cdot I(T). \qquad (4)$$

The integral in (4) can be taken explicitly (Gradshtein and Ryzhik, 1963):

$$I(T)=\frac{\alpha}{t}\int_0^T\frac{d\tau}{(1+\overline{\tau})^{\alpha+1}}=\frac{\alpha}{t}\left[-\frac{t}{\alpha}\frac{1}{(1+\overline{\tau})^{\alpha}}\right]\Bigg|_0^T=1-\frac{1}{(1+\overline{T})^{\alpha}}, \qquad (5)$$

where $\overline{\tau}=\tau/t$, $\overline{T}=T/t$.

As follows from (5), $\lim\limits_{T\to\infty}I(T)=1$; extending the square pulse width in the limit will lead to the field $E_0(t)$ in (4), which corresponds to infinite step turn-off; at small t, $\lim\limits_{t\to 0}I(t)=1$ as well. Therefore, equation (4) is valid also at early times $t<T$ because the turn-on effect is minor. This inference is confirmed by calculations (Fig. 6). Fig. 6*a* shows voltage decay (solid line) at an infinite step transmitter waveform, a computed curve (crosses) for a 50 ms square pulse, and a curve (dash line) obtained by calculations using equation (4). The curve on the right (Fig. 6*b*) is relative deviation of the exact and approximate voltage calculated for a square pulse, which is within 0.1 %. Thus, equation (4) can be used successfully instead of calculating a convolution integral for the square waveform.

Since it is possible to construct any particular waveform out of several short pulses, equation (4) can be generalized for a waveform described by the arbitrary function $q(\tau)$, provided that $q(0)=q(T)=0\mu_X$:

$${}^{q}E(t)\approx E_0(t)\frac{\alpha}{t}\int_0^T\frac{q(\tau)\,d\tau}{(1+\overline{\tau})^{\alpha+1}}. \qquad (6)$$

Figure 7 shows calculated voltage decay curves for the $q(t)=\sin\frac{\pi t}{T}$ waveform (T = 50 ms, loop-loop configuration). The curves in *a* are for the cases of infinite step (solid line) and half-sine (dash line and crosses) waveforms; the dash line and crosses are, respectively, calculated exact and approximate solutions to equation (6). The panel *b* shows

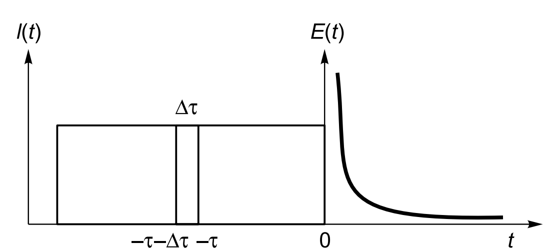

Fig. 4. Square waveform of transmitter turn-off.

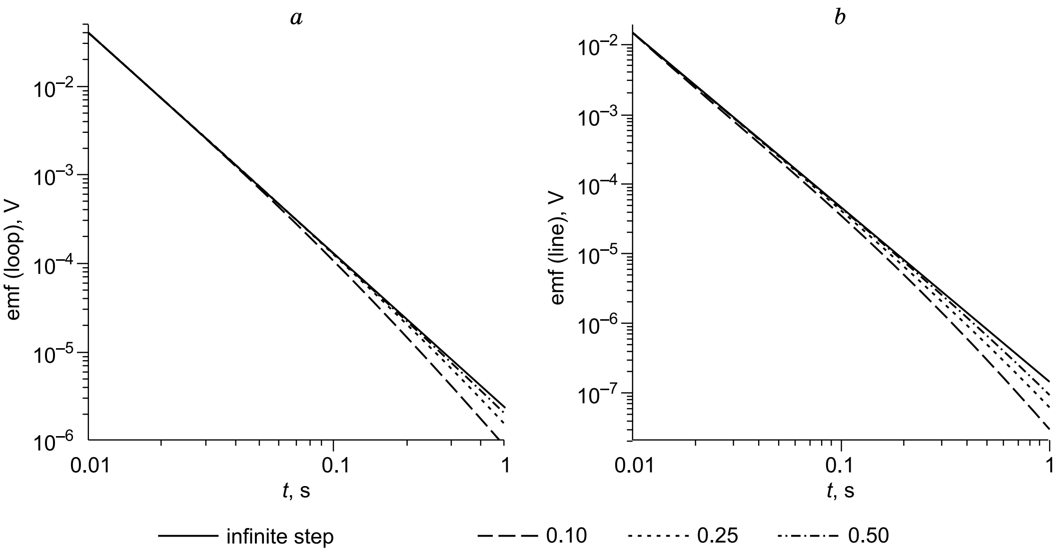

Fig. 5. Effect of turn-off time on TEM responses: loop-loop (*a*) and line-loop (*b*) configurations. Curves are labeled according to turn-off time for square current waveform: 0.10 s, 0.25 s, 0.50 s.

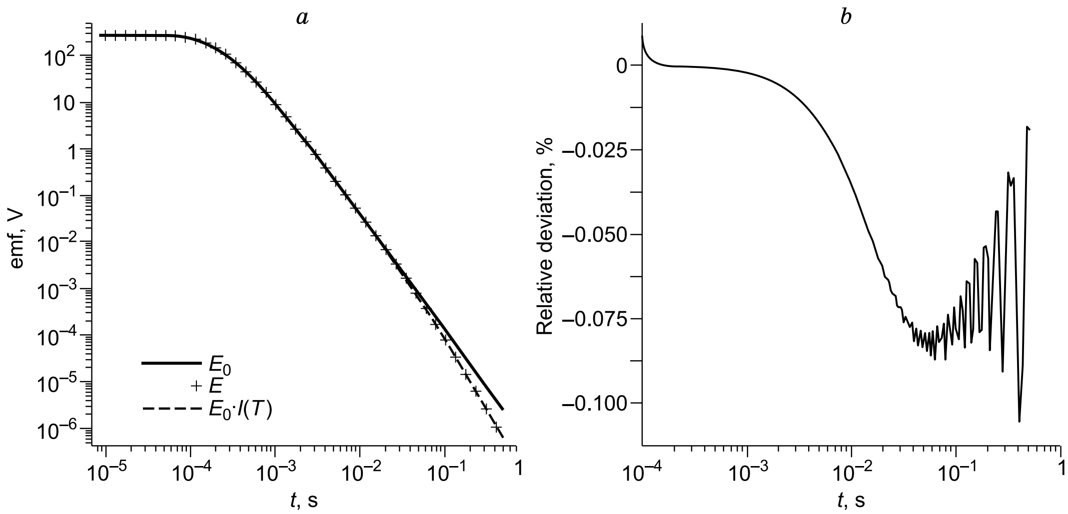

Fig. 6. Exact and approximate calculated responses to square turn-off. *a*, E_0 refers to infinite step; *E* refers to square waveform, calculated by convolution; $E_0I(T)$ refers to square waveform, calculated using equation (4); *b*, relative deviation of exact and approximate voltage $\dfrac{\left[E-E_0I(T)\right]}{E}\cdot 100\%$.

relative deviation of exact and approximate voltage decay curves for a special pulse $q(t)$. As one can see in Fig. 7*b*, approximation (6) does not work at early times but is valid at late times; relative deviation of the curves reduces to <1 % at >10 ms.

COMPENSATION METHOD

Equation (6) for late time responses at an arbitrary transmitter waveform does not provide many opportunities for improving the resolution of TEM surveys because it does not include the properties of the subsurface. Actually, according to equation (6), the current waveform loses influence at latest times but some corrections to the step turn-off are possible at early times. Previously it was suggested to improve the resolution using a special transmitter waveform, in the successfully implemented compensation method (Isaev, 1983; Isaev and Trigubovich, 1983).

In that method, the final turn-off is preceded by a short pulse opposite in polarity to the main current, which produces sign reversal in voltage decay curves (in-loop responses). The responses within the narrow interval of sign reversal contain greater contributions from anomalous objects. The details can be explained using a model of a uniform layer (h = 1200 m, ρ = 10 Ohm × m) which encloses a

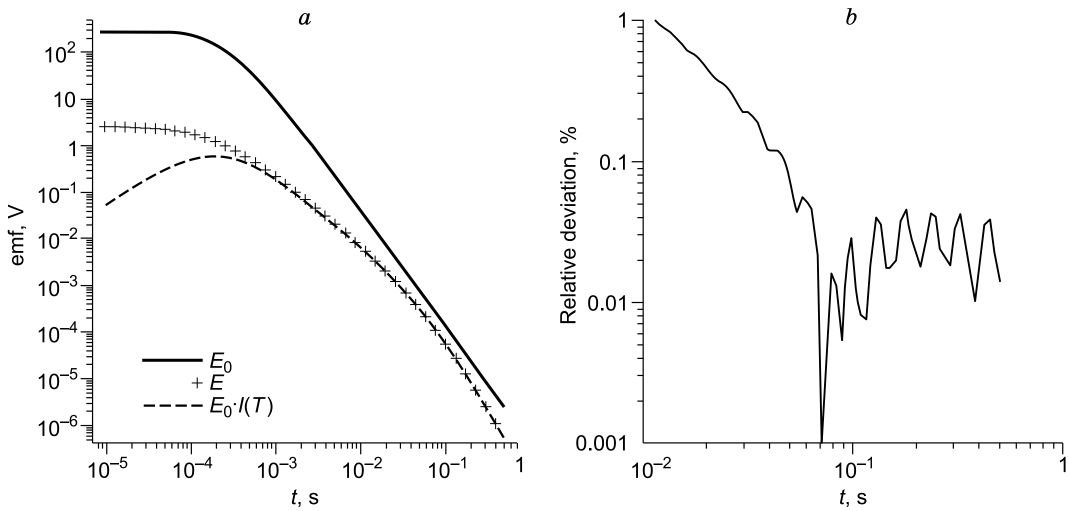

Fig. 7. Responses to turn-off of a special waveform, exact and approximate calculations. *a*, E_0 refers to infinite step; *E* refers to square waveform, calculated by convolution; $E_0I(T)$ refers to square waveform, calculated using equation (6); *b*, relative deviation of exact and approximate voltage $\frac{\left[E - E_0 I(T)\right]}{E} \cdot 100\%$.

50 m thick conductor (2 Ohm × m) at a depth of 1000 m. The normal and total fields obtained with and without compensation are compared in Fig. 8. The panel *b* shows a 500 ms negative main pulse and a 20 ms positive compensating pulse, and the signal is analyzed within the interval of sign reversal. Inasmuch as data in a single curve is insufficient and poorly reliably, it was suggested to apply several (up to ten) main pulses with compensation pulses of different durations (Fig. 9). The method was implemented and tested in Australia, with the use of specially designed instruments. It

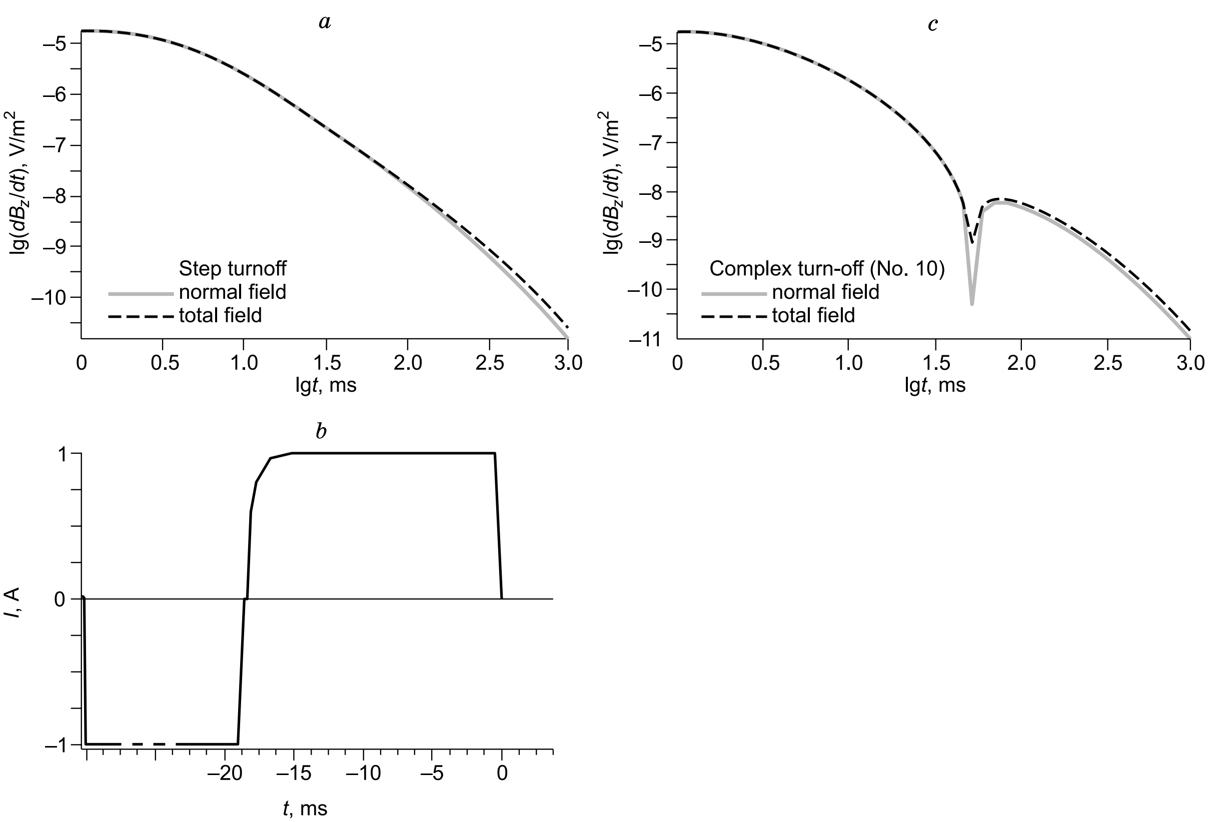

Fig. 8. Compensation method of TEM surveys. Normal and total fields, compared: step turn-off (*a*); complex waveform pulse (*b*); complex turn-off (*c*).

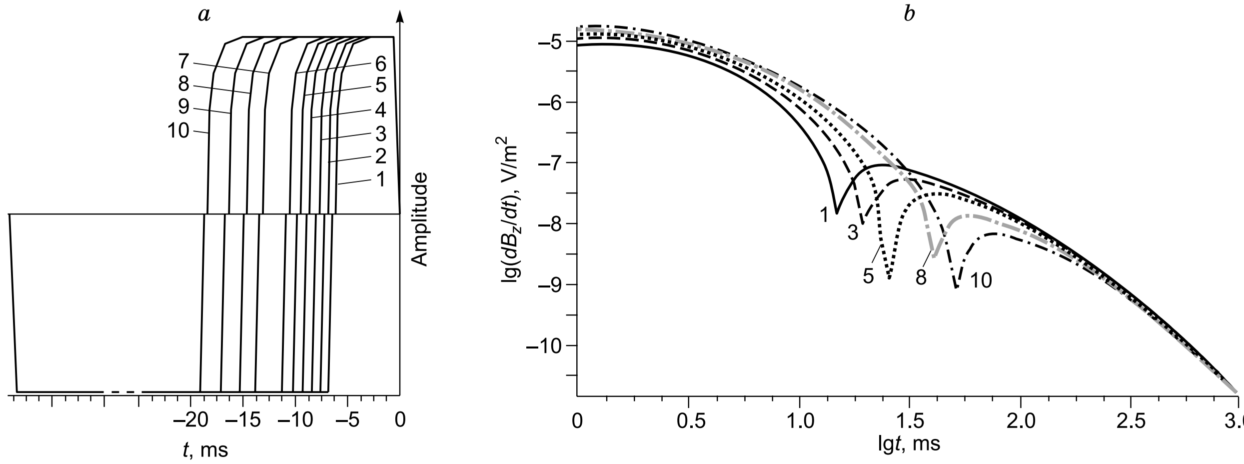

Fig. 9. Series of transmitter pulses (*a*) and responses (1, 3, 5, 8, 10) (*b*).

allows using more diverse and independent data, but at the costs of more sophisticated instrumentation. It was not a breakthrough though, as one may judge proceeding from equation (6). The project was abandoned in the early 1990s because of objective and subjective political and economic circumstances.

TRANSMITTER WAVEFORM DEPENDENCE OF THE ELECTRIC FIELD (TM) COMPONENT

Now we consider the effect of a complex transmitter waveform on voltage decay for the electric (TM) field. It can be excited by a vertical electric dipole (VED) or a circular electric dipole (CED) from the ground surface (Fig. 10). The behavior of the TM-polarized field is quite different from that of the TE component. The respective late-time ($t \to \infty$) response of a two-layer earth with a resistive lower layer ($h_1 = h$, $\rho_1 = \rho$, $\rho_2 = \infty$) to step turn-off is

$$E_\varphi^0(t) \cong M_z \cdot \frac{3r\rho}{2\pi h} \cdot \left(\frac{\mu_0 h}{2\rho t}\right)^4, \tag{7}$$

and in the case of a VED or a CED (radial) source, it is

$$E_r^0(t) \cong C \cdot \frac{r\rho}{\pi h^3} \cdot \left(\frac{\mu_0 h}{2\rho t}\right)^2 \cdot \exp\left(-\frac{\pi^2 \rho t}{\mu_0 h^2}\right), \tag{8}$$

where $C = Idz_0 \cdot z_0$ for VED and $C = Ib^2/4$ for CED; Idz_0 and z_0 refer to the moment and the position of VED; I and b are the current and radius of CED (Mogilatov, 1997, 2014).

Then, it is easy to constrain the waveform for an arbitrary pulse $q(t)$ in the case of VED or CED:

$${}^qE_r(t) = E_r^0(t) \cdot \int_{\tau_1}^{\tau_2} \frac{dq(\tau)}{d\tau} \exp\left(\frac{\pi^2 \rho \tau}{\mu_0 h^2}\right) d\tau\,. \tag{9}$$

If the arbitrary pulse is defined within a limited set of times (a_i, τ_i, $i = 1, 2,\ldots, N$), which are assumed to change linearly rather than stepwise, equation (9) becomes

$$\begin{aligned} {}^qE_r(t) &= E_r^0(t) \cdot \frac{\mu_0 h^2}{\pi^2 \rho} \\ &\times \sum_{i=1}^{N-1}\left[\exp\left(\frac{\pi^2 \rho \tau_{i+1}}{\mu_0 h^2}\right) - \exp\left(\frac{\pi^2 \rho \tau_i}{\mu_0 h^2}\right)\right] \cdot \frac{a_{i+1} - a_i}{\tau_{i+1} - \tau_i}\,. \end{aligned} \tag{10}$$

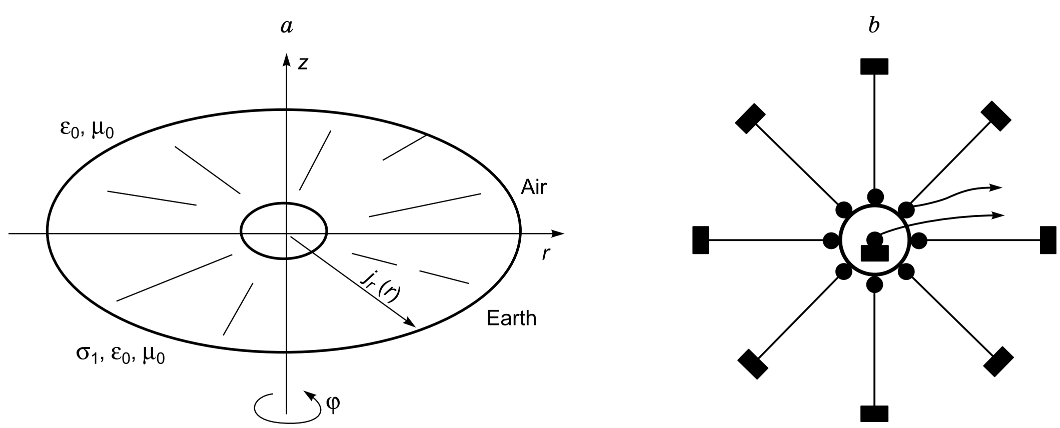

Fig. 10. Ideal (*a*) and real (*b*) circular electric dipole (radial source).

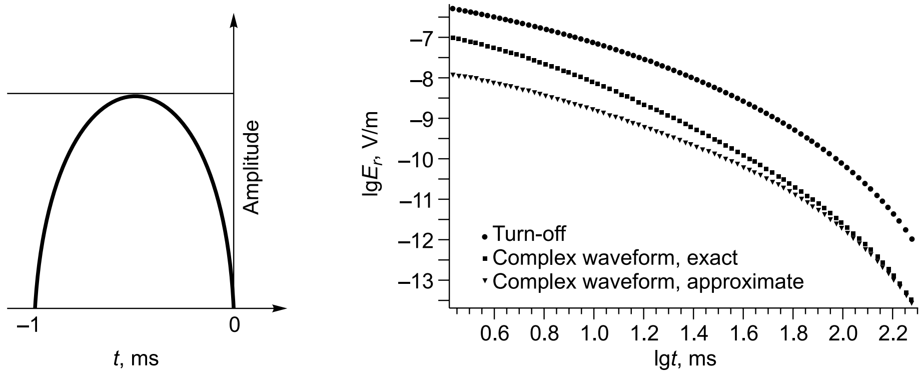

Fig. 11. Illustration to (10). Calculations, compared. Turn-off, complex waveform, exact; complex waveform, approximate.

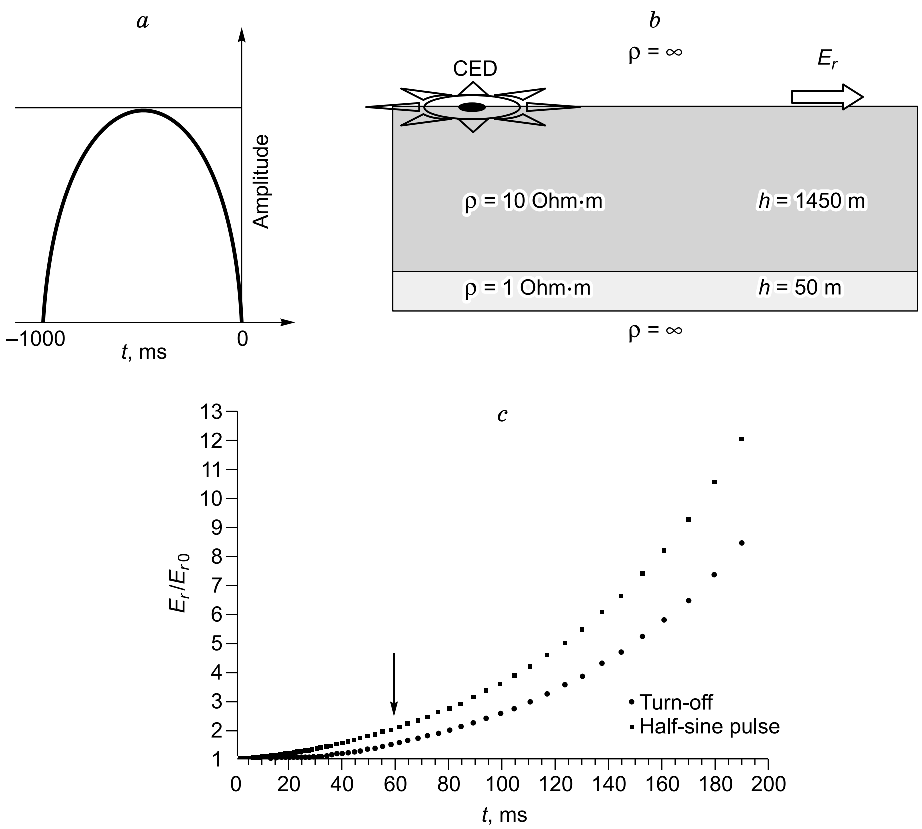

Fig. 12. Effect of current waveform on late-time anomalous response. *a–c*, see text for explanatitons.

The use of equation (10) is illustrated in Fig. 11, where an approximate calculation with (10) for a two-layer earth ($h_1 = 1500$ m, $\rho_1 = 10$ Ohm × m, $\rho_2 = \infty$) is compared with an exact calculation for a half-sine pulse.

An important feature of equation (10) for a loop source, unlike (6), is that the response depends on transmitter waveform at late times as well, and is related to geoelectric parameters of the subsurface. This allows managing the responses in order to highlight the contribution of anomalies. The total and normal fields are compared in Fig. 12 for the cases of step and half-sine waveforms (Fig. 12*a*). The relative contribution of the conductor (Fig. 12*b*) increases with time (Fig. 12*c*) as a consequence of late-time exponential decay, especially in the case of half-sine pulses.

Note that the signal is realistically measurable within a limited range (shown by arrow in Fig. 12), but the general inference remains valid.

CONCLUSIONS

The problem of transmitter waveform control on voltage decay patterns, at both late and early times, has been solved in pulse induction resistivity surveys by the use of the respective software. However, express approximate calculations are always required in field data processing. Improving the resolution of TEM soundings by choosing complex pulse shapes remains a challenge. As we have shown, the potentiality of surveys with the TE polarization (magnetic) component of the field is limited in this respect because the transmitter waveform effect is vanishing at late times.

The TM component has been used since recently, which has incurred many particular problems in data acquisition and interpretation. TM-based surveys open a new perspective of the old question of transmitter waveforms in TEM soundings, which seemed of no interest in the classical induction surveys.

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Editorial responsibility: A.D. Duchkov