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Current turn-off in an ungrounded horizontal loop: experiment and theory

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Abstract

An ungrounded horizontal loop, a common transmitter type in TEM surveys, makes up a system with distributed parameters with the earth under it. It can be simulated by an equivalent circuit with lumped parameters at late times and/or low frequencies, but at early times commensurate with the period of free current oscillations, the lumped circuit model fails to account for experimental data. At high frequencies and/or early times, the wire, in combination with the underlying earth, forms a transmission line in which current behaves according to the wave equation. This model allows calculating the current at any time and at any loop point with reference to the theory of long transmission lines. At early times, the loop self-responses depend on near-surface resistivity and environment and its primary magnetic field differs from that predicted by the classical theory of TEM surveys. Therefore, inversion of early-time rerponse in terms of the conventional TEM system model is meaningless. However, as illustrated with a loop shunted by a matching resistor, the loop model as a combination of two transmission lines enables the inversion of the early-time current response in terms of the line parameters and near-surface resistivity.

Keywords: TEM surveys; horizontal loop; current turn-off; early times; transmission line; inversion

Introduction

Ungrounded horizontal loop, common basic constituents of TEM sounding systems, is used to excite the primary field and to measure the secondary magnetic field. The turn-off of transmitter current induces a vortex electric field and related eddy currents in the underlying earth. As the primary field disappears, the receiver measures the secondary magnetic field or most often its time derivative.

The measured earth response is convolved with the transmitter and receiver self responses (Asten, 1987; Zakharkin, 1981), and the features and duration of the transmitter current turn-off and the receiver self response are to be included in forward modeling and inversion of transients. The effect of the receiver self response on TEM data was the subject of many publications (Efimov, 1976; Kozhevnikov and Plotnikov, 2004; Nikolaev et al., 1988; Qian, 1985; Schamper et al., 2014; Vishnyakov and Vishnyakova, 1974; Yu et al., 2014, etc.). The effects of the current turn-off duration and waveform, and ways of taking them into account in modeling were likewise largely discussed (Asten, 1987; Fitterman and Anderson, 1987; Raiche, 1984; Sokolov et al., 1978). The intrinsic parameters of a loop are commonly modeled in terms of an equivalent lumped circuit.

Ever earlier measurement times in shallow TEM soundings are becoming increasingly important through recent 10–15 years. Shorter initial recording time requires shorter turn-off duration in the transmitter, but there are both engineering (Plotnikov, 2014) and fundamental limitations on this way. The latter is, namely, that the lumped-circuit model fails to account for experimenal data (Kozhevnikov, 2006; Kozhevnikov and Nikiforov, 1998, 2000). The thus far known experimental results explainable only in terms of a distributed system are as follows:

1. The input impedance of a loop depends on frequency in the same way as that of a long transmission line shorted at the output (Kozhevnikov, 2006; Kozhevnikov and Nikiforov, 1998, 2000).

2. The current switch-off induces attenuating standing waves of current and voltage in an open loop (Helwig and Kozhevnikov, 2003; Kozhevnikov, 2006; Kozhevnikov and Nikiforov, 1998, 2000).

3. The current turn-off is neither simultaneous nor synphase along the loop wire, and the delay at different points being proportional to their distance to the loop input terminals (Helwig and Kozhevnikov, 2003; Kozhevnikov, 2009).

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These results mean that at early times and/or high frequencies the loop, together with the near-surface under it, behaves as a *long transmission line* (Kozhevnikov, 2006, 2009; Kozhevnikov and Nikiforov, 1998, 2000). Thus the current turn-off in an ungrounded horizontal loop can be modeled using the transmission lines theory. The principles of this modeling discussed in detail in (Kozhevnikov, 2006, 2009) are summarized below.

A loop model as a combination of two long transmission lines

A transmission line made of a wire and the earth it lies upon seem to have little in common with an ungrounded horizontal loop. However, by symmetry, a loop can be presented as two serially connected identical lines with their meeting common point grounded. The current/voltage source likewise can be simulated by a combination of identical serially connected sources with a grounded common point (Fig. 1). A square loop of a wire length P, lying on the surface and connected to a transmitter (Fig. 1*a*), is equivalent to a serial pair of lines, each $P/2$ long (Fig. 1*b*). Correspondingly, a source with the output voltage U and the internal resistance R_i (2 in Fig. 1*a*) splits into two, each having the output voltage $U/2$ and the self resistance $R_i/2$ (Fig. 1*b*).

The system in Fig. 1*b* being symmetrical, the point O and that at the distance $P/2$ have the same potential, and their connection to the earth does not affect the voltage and current distribution in the loop. Therefore, the early-time (and/or high-frequency) parameters of an ungrounded loop with the perimeter P can be estimated as those for an output-shorted line of the length $l = P/2$ (Fig. 1*c*).

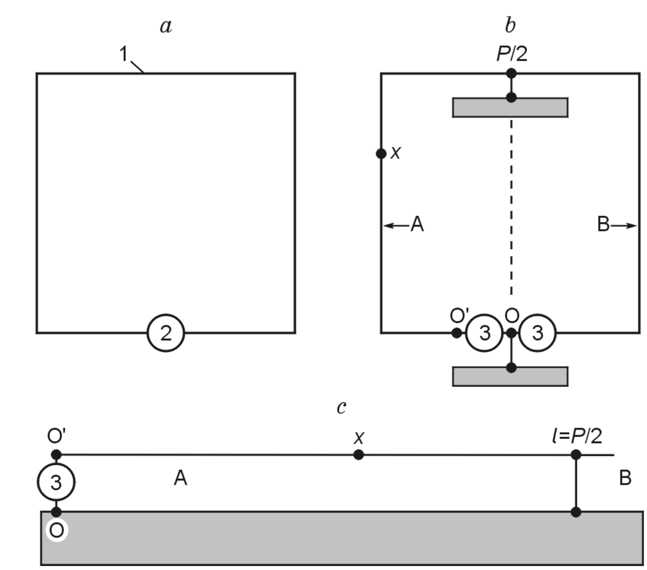

Fig. 1. Ungrounded horizontal loop 1 and current source 2 (*a*); same loop and source presented as two identical transmission lines A, B and sources 3 (*b*); output-shorted line of the length $l = P/2$ (*c*).

This approach applied to the TEM system is illustrated in Fig. 2: a transmitter loop with the steady current I_0 is connected to the voltage source U and the switch (Fig. 2*a*), and the loop input is shunted by a matching (damping) resistance R_1. As the transmitter is switched off, the input current zeroes down almost instantaneously. Each of the two lines making the loop (Fig. 2*b*) has at its inputs a source with the voltage $U/2$, the resistor $R_1/2$ and a switch. At $t = 0$ each switch disconnects its line from its voltage source. The points O and $P/2$ having the same potential by symmetry can be grounded, and the loop current turn-off problem becomes that for a transmission line (Fig. 2*c*).

In the transmission lines theory, the line is exhaustively described by propagation constant $\dot{\gamma}$ and characteristic impedance $\dot{Z}$, which in the general case are complex and frequency-dependent. The propagation constant $\dot{\gamma}$ is

$$\dot{\gamma} = \alpha + j\beta,$$

where α is the attenuation constant and β is the phase constant, both having the same dimension 1/m, $j = \sqrt{-1}$.

With known per-unit-length inductance L, capacitance C, resistance R, and insulation conductance G, α and β are found as (Baskakov, 1980; Simonyi, 1956):

$$\alpha = \left\{ \frac{1}{2}(RG - \omega^2 LC) + \frac{1}{2}\left[(R^2 + \omega^2 L^2) \times (G^2 + \omega^2 C^2) \right]^{1/2} \right\}^{1/2},$$

$$\beta = \left\{ \frac{1}{2}(\omega^2 LC - RG) + \frac{1}{2}\left[(R^2 + \omega^2 L^2) \times (G^2 + \omega^2 C^2) \right]^{1/2} \right\}^{1/2},$$

where ω is the angular frequency of current and voltage in the line.

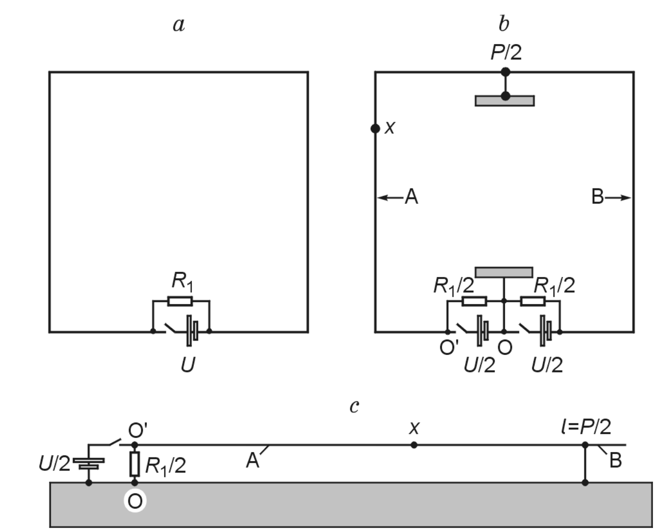

Fig. 2. Ungrounded horizontal loop 1 and voltage source U, switch, and shunt resistance R_1 (*a*); same loop, current source, and shunt resistor presented as two identical lines A, B, sources, and resistors (*b*); output-shorted line A (*c*).

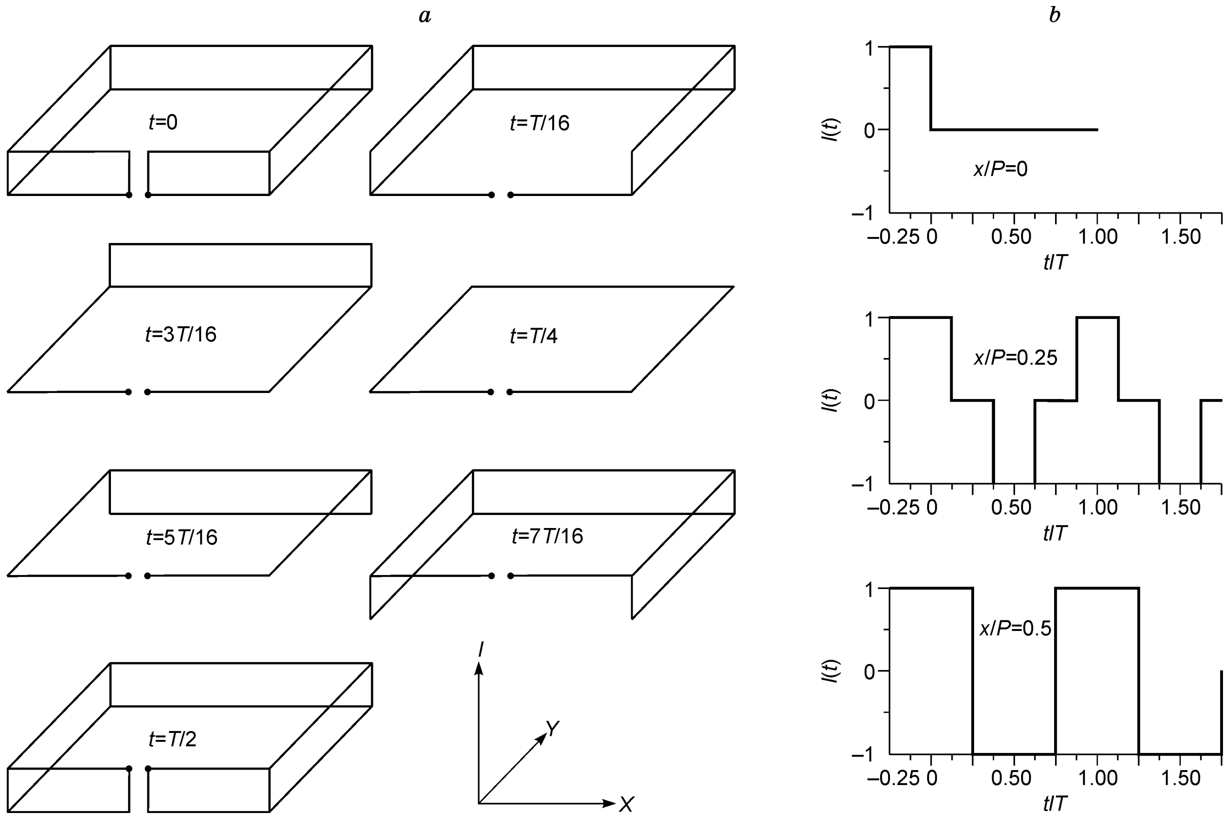

Fig. 3. Current turn-off in an ideal open ($R_1 = \infty$) loop: *a*, snapshots of current distribution along the loop at fixed times; *b*, current turn-off waveforms at some loop points. Switch-off occurs at $t = 0$.

It is convenient to express the impedance $\dot{Z}$ as a product of the magnitude Z_0 and the phase constant ψ:

$$\dot{Z} = Z_0 e^{j\psi},$$

$$Z_0 = \left(\frac{R^2 + \omega^2 L^2}{G^2 + \omega^2 C^2}\right)^{1/4},$$

$$\psi = \arg \dot{Z} = \frac{1}{2} \arctan \frac{G/(\omega C) - R/(\omega L)}{1 + (GR)/(\omega^2 LC)}.$$

Turn-off in an ideal loop: free oscillations

Comprehensive analysis of lines making a loop, with due regard for the dependence of their parameters on frequency and earth conductivity, is a difficult task. However, even a simple model of a loop as a combination of two ideal transmission lines (free from losses, frequency dependence, and near-surface conductance effects) demonstrates the difference between a loop and a lumped circuit.

First it is pertinent to consider the current turn-off in a nonshunted ($R_1 = \infty$) loop. A convenient way to see what happens at different wire points of an ideal loop after the voltage source is switched-off from the loop is to present the transient current as a superposition of current waves propagating in opposite directions in a transmission line made by the wire and the earth below it (Shalyt, 1982). If one loop terminal is at the origin and the distance counted from it along the wire corresponds to the coordinate x (Figs. 1*a*, 2*a*), the coordinate of the other terminal equals the loop perimeter P. In each of the two transmission lines (Fig. 3*a*), switch-off produces, a negative step current wave having the amplitude I_0 and traveling from the loop input to its middle point ($x = P/2$). As this wave reaches the virtually grounded midpoint, there arises another reflected wave traveling from the midpoint back to the input. The total current in the line is the sum of the steady current and two waves traveling, respectively, from the loop input to the midpoint and back. The reflected wave reflects again from the open ($R_1 = \infty$) loop input; since then the total current in the wire becomes a sum of three current waves and steady current. Then other reflections occur, the superposition of waves traveling forward and back produces a standing wave with the period T, and the process becomes periodical, continuing for an indefinitely long time.

Snapshots of current distribution $I(x)$ along the perimeter of an ideal loop (Fig. 3*a*) and $I(t)$ plots for different loop points (Fig. 3*b*) show that, contrary to the prediction of the classical theory of TEM prospecting, the turn-off is not simultaneous along the wire but has some lag. As a result, the early-time current distribution in the loop is symmetrical about the Y axis but not about the X axis. Therefore, the transient and/or frequency response of the loop can in principle depend on the place where the transmitter is connected to the loop in the case of asymmetrical environment (e.g., an electrically asymmetrical earth).

Difference between an ideal and an actual loops

The actual lines are subject to losses and frequency dependence of their parameters. Since there is extensive literature available on frequency-domain modeling for these lines (Baskakov, 1980; Johnson and Graham, 1993), it appears reasonable to find first a frequency-domain solution and then to transform it into the time domain.

The current turn-off waveform in a loop can be modeled assuming that the capacitance C and the insulation conductance G per unit length are independent on the frequency ω and the earth's resistivity ρ while the per-unit-length resistance R and inductance L depend on ρ and ω, which the modeling has to allow for (Kozhevnikov, 2009).

Measurements of current turn-off at several points along a 200×200 m nonshunted loop made of a standard geophysical copper wire (Kozhevnikov, 2006, 2009) shows that the wire complex impedance (per unit length) includes three terms:

$$\dot{Z}_\mathrm{w} = R_\mathrm{w} + \dot{Z}_1 + \dot{Z}_2. \quad (1)$$

The wire resistance R_w equals its dc resistance (R_dc) at low frequencies but is affected by the skin effect in the wire at high frequencies. This effect can be accounted for as follows (Simonyi, 1956):

$$R_\mathrm{w} = R_\mathrm{dc}\left(1 + \frac{\theta^4}{3}\right) \text{ for } \theta < 1, \quad (2a)$$

$$R_\mathrm{w} = R_\mathrm{dc}\left(\theta + \frac{1}{4} + \frac{3}{64\theta}\right) \text{ for } \theta > 1, \quad (2b)$$

where $\theta = (r_\mathrm{w}/2\delta_\mathrm{w})$; $\delta_\mathrm{w} = \sqrt{2/(\omega\mu_\mathrm{w}\sigma_\mathrm{w})}$; r_w is the wire radius; μ_w is the magnetic permeability of the wire; and σ_w is its conductivity; R_w at $\theta = 1$ is found as a mean of two values calculated with Eqs. (2*a*, *b*).

The second term $\dot{Z}_1$ in (1) accounts for return (image) current in the earth (Wang and Liu, 2001),

$$\dot{Z}_1 = j\omega\frac{\mu_0}{2\pi}\ln\frac{2(h+p)}{r_\mathrm{w}}.$$

Here, $p = \delta\,(2j)^{-1/2}$, $\delta = \sqrt{2\,(\sigma\omega\mu)}$, where σ is the conductivity and μ is the earth's magnetic permeability.

Finally, the third term ($\dot{Z}_2$) refers to the part of the per-unit-length impedance of the wire due to the inductance between the lines forming the loop. For a uniform conductive earth (Kozhevnikov, 2009; Sobolev and Shkarlett, 1967), $\dot{Z}_2$ is assumed to be

$$\dot{Z}_2 = \frac{6\times10^{-7}\,\omega a}{\beta^2}\,3\left(3 - \sqrt{9 + 4j\beta^2}\right),$$

where $\beta = a\sqrt{\omega\sigma\mu_0}$, $a = A/\pi$, A is the side length of a square loop.

The relative contribution of $\dot{Z}_2$ to $\dot{Z}_\mathrm{w}$ is smaller than that of the image current, but $\dot{Z}_2$ depends on earth conductivity, which makes it possible to estimate the resistivity and maybe also chargeability (Kozhevnikov, 2011) of the near-surface.

The wire resistance and inductance per unit length, with regard to current in the earth and the skin effect in the wire, are obviously

$$R = \mathrm{Re}\,\dot{Z}_\mathrm{w},\ L = \frac{\mathrm{Im}\,\dot{Z}_\mathrm{w}}{j\omega}.$$

With these parameters being known, the solution for the line current can be obtained in the frequency domain and then converted into the time domain by the Fourier transform. Thus the current turn-off waveform becomes modeled at any point of the line and loop, respectively.

Free current oscillations in a transmitter (the so-called ringing) have implications for the parameters that describe the loop as a distributed system. Usuallu, current ringing is most often considered as noise to be reduced by shunting the loop with matching resistance (Vanchugov and Kozhevnikov, 1998), or by special processing techniques (Sharlov et al., 2010). However, ringing can provide information on shallow subsurface (Kozhevnikov, 2011; Vakhromeev et al., 1991). Therefore, studies of how current oscillations in the transmitter loop depend on the TEM instrument, loop size and geometry, landscape, and weather, as well as the near-surface resistivity, may be of academic and practical interest for TEM prospecting.

Current turn-off in a loop: matching mode

The oscillating current turn-off process can be stopped by the matching of the loop when there is no reflection from the open loop input (Fig. 4). Matching can be achieved with an external resistor $R_1 = 2Z_0$, connected to the loop input, which is most often 350–500 Ohm for a standard geophysical copper wire, with a cross section area of a few mm^2 laid on the ground surface (Helwig and Kozhevnikov, 2003; Kozhevnikov, 2006, 2009; Kozhevnikov and Helwig, 2014; Kozhevnikov and Nikoforov, 1998, 2000).

Figure 4*a* shows snapshots of current in an ideal loop shunted by the matching resistor R_1 (not in the picture) at different times after switch-off; Fig. 4*b* illustrates the current turn-off waveforms at different loop points. Like the case of $R_1 = \infty$ (Fig. 3), there is also a delay, and the current turn-off waveform changes as a function of x. The total turn-off time in an ideal loop, at perfect matching, is $T/2$ (Fig. 4), and will be obviously longer for an actual loop.

The delay (illustrated for an ideal loop in Fig. 4) appears in the actual loop as well. See, for instance, switch-off current waveforms for a 100×100 m loop ($R_\mathrm{dc} = 13.25 \times 10^{-3}$ Ohm/m, $G \approx 10^{-11}$ S/m) at the points $x = 0$, 100 and 200 m obtained at a test site of the Institute of Geophysics and Meteorology of Cologne University (Helwig and Kozhevnikov, 2003). The current waveforms were studied using a shunt resistor connected serially with the loop wire at x; the

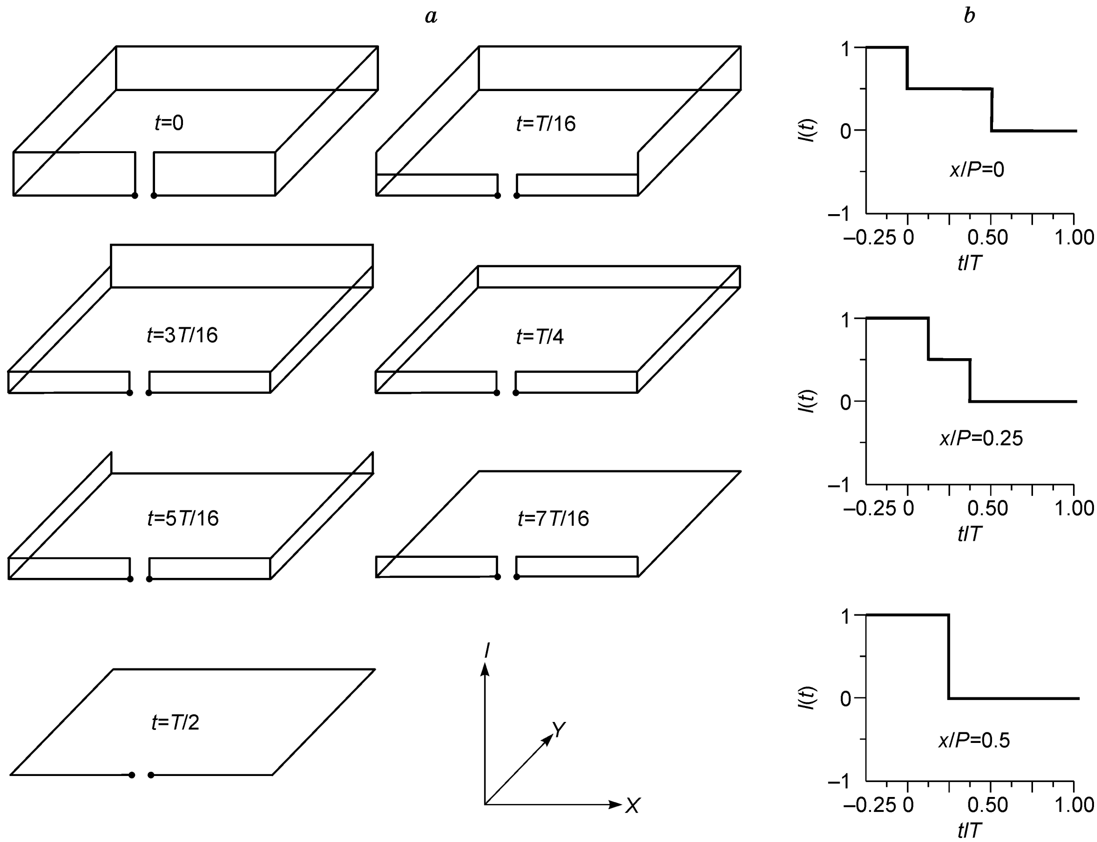

Fig. 4. Current turn-off in an ideal loop with shunt resistance equal to double characteristic impedance of the earth-wire transmission line (matching mode): *a*, snapshots of current distribution along the loop at fixed times; *b*, current turn-off waveforms at some loop points.

voltage across the shunt resistor was recorded by a battery-powered digital oscillograph. Almost perfect matching was provided by a 490 Ohm resistor connected in parallel with the loop input.

For comparison, Fig. 5*b* shows the current turn-off waveforms of Fig. 4*b* for the respective points of the ideal loop. The predicted and measured waveforms do look quite similar though there are some differences in details. Because of frequency dispersion of the actual loop parameters, the patterns at each point are smoother than those for the ideal loop, except for the the loop input where there are small negative current spikes.

The current turn-off waveforms predicted by modeling the loop as a combination of two tansmission lines (Fig. 5*a*) correspond to the optimal values of the per-unit-length wire capacitance C and the resistivity ρ of the earth. The optimal model was searched by manual fitting, which resulted in the best fit between the observed and computed data at $\rho \approx 5$–10 Ohm·m and $C = 4.7 \times 10^{-11}$ F/m.

The reason why the short negative current pulses appear near the loop input remains unclear. They may result from capacitance coupling between the wire and the input of the measuring unit (an oscillograph in the reported case). These effects, which fall into the category of intersystem interference, are beyond the present consideration and are worth a separate study.

Discussion

The model simulating a loop as a combination of two transmission lines explanes the current turn-off but also raises questions.

The current turn-off duration and waveform for $I_0 = 0.09$ A at the midpoint ($x = 200$ m) of a 100×100 m loop was modeled (Fig. 6) as a function of earth resistivity (Fig. 6*a*), per-unit-length wire capacitance C (Fig. 6*b*) and the matching resistor R_1 (Fig. 6*c*). In each panel, the respective parameter is allowed to vary while all others remain constant.

The illustration of the effects of different parameters is spectacular and seems to need no comments, but there is one point worth of special note. At fixed earth resistivity and wire capacitance, it is always possible to find R_1 providing the shortest total turn-off time (Fig. 6*c*). However, the capacitance depending on the effective height of the wire over the ground, terrain, vegetation, humidity, earth resistivity, etc. can be different in another locality (Kozhevnikov, 2009). Thus, the shunt resistor being constant ($R_1 = 400$ Ohm), the transient process, which depends on the earth resistivity (Fig. 6*a*) and wire capacitance (Fig. 6*b*), will also change. Therefore, a shunt resistance selected for some sounding site will no longer provide optimal matching elsewhere.

This does not mean that shunting is pointless. As field practice shows, it is possible to select a shunt resistance such that the current turn-off is quite short and not oscillating

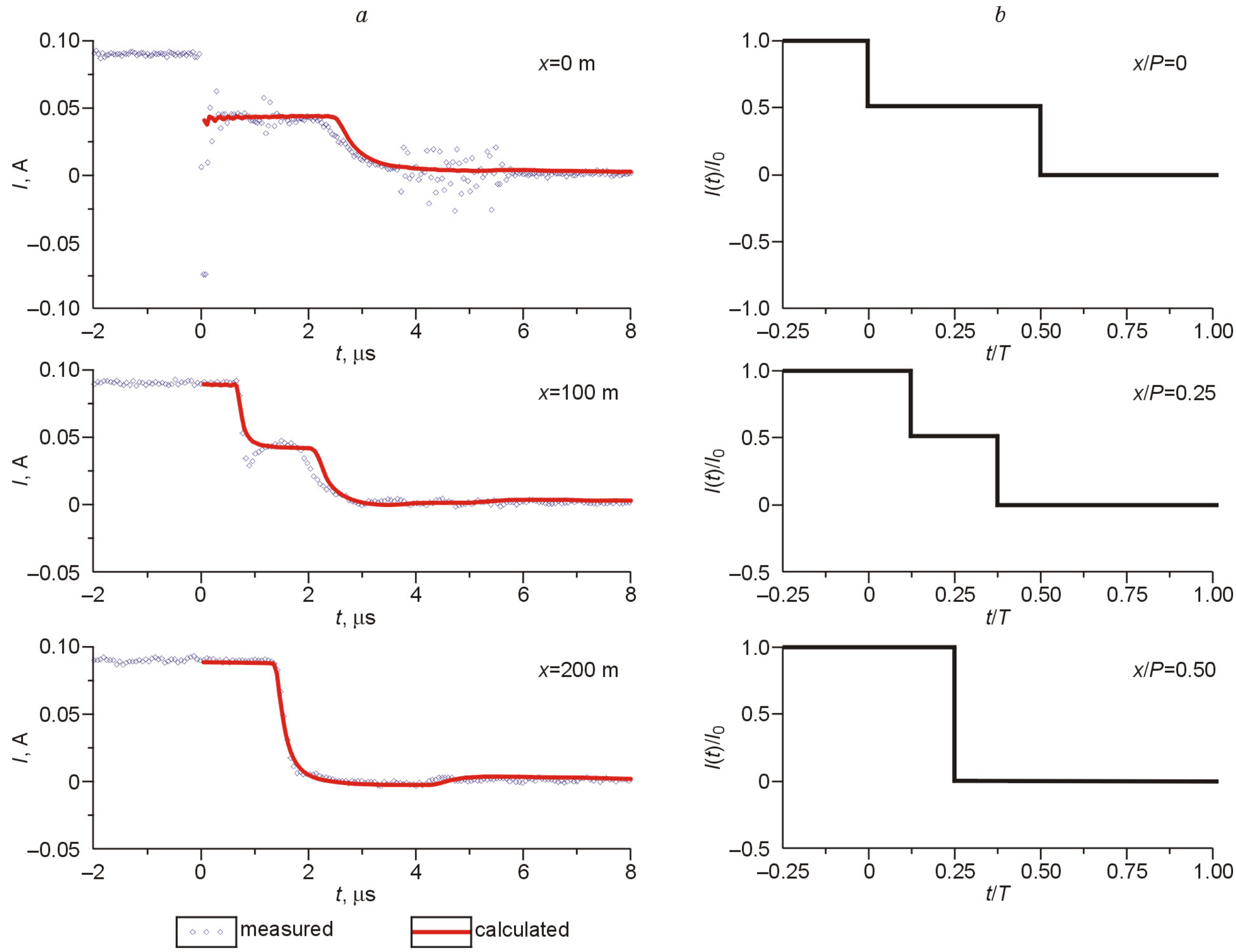

Fig. 5. Current turn-off waveforms for an actaul 100 × 100 m loop at $x = 0$, 100 m, and 200 m (*a*) and an ideal loop (*b*): matching mode.

(Vanchugov and Kozhevnikov, 1998). However, this does not work at very early times: moving to ever earlier times is fundamentally limited. The reason is that the early-time loop parameters depend on local resistivity and environment, including weather (Kozhevnikov, 2011), and the concept of a "primary source field" looses sense. Thus it is impossible to find a near-surface model providing appropriate explanation for the transient process in terms of the conventional theory of TEM soundings, which assumes that the primary field source is independent of the earth properties. Such a model can be found beyond the conventional theory, by considering a loop and the ground below it as a single distributed system (Kozhevnikov, 2009).

Note in conclusion that the reported modeling results were obtained assuming that a loop is disconnected from the current source instantaneously and the transient process is further controlled uniquely by the parameters of the lines and the matching resistor. As a rule, voltage across the loop terminals and, correspondingly, across the switch, is limited by oppositely connected Zener or avalanche diodes and other elements to protect the switch from overvoltage. The limiting voltage U_{lim} is commonly of the order of hundreds of volts or more (e.g., $U_{\mathrm{lim}} = 400$ V in the *FastSnap* system for shallow TEM soundings; http://www.sibgeosystems.ru/hardware/FastSnap/). If current in a loop exceeds 1–2 A, the switch-off voltage spikes at loop inputs are limited to U_{lim}. This protects switches from breakdown but increases the total switch-off time (Ott, 1976), which in its turn leads to increase in earliest measurement time and sounding depth. Therefore, shallow subsurface is usually sounded at small current.

The reported experiments aimed at investigating the current turn-off as controlled by loop parameters and by properties of the underlying earth rather than by the TEM system electronics. The steady current in the experiments was about 0.1 A, and the elements preventing overvoltage were unnecessary, which allowed using the theory of distributed linear circuits to interpret the experiment results.

Conclusions

An ungrounded horizontal loop commonly used as a transmitter in TEM surveys, together with the earth under it, make up a distributed system. At late times and/or low frequencies this system can be modeled in terms of an equivalent circuit with lumped parameters. However, the equivalent loop model fails to account for experiment data at times commensurate with the period of free current oscilla-

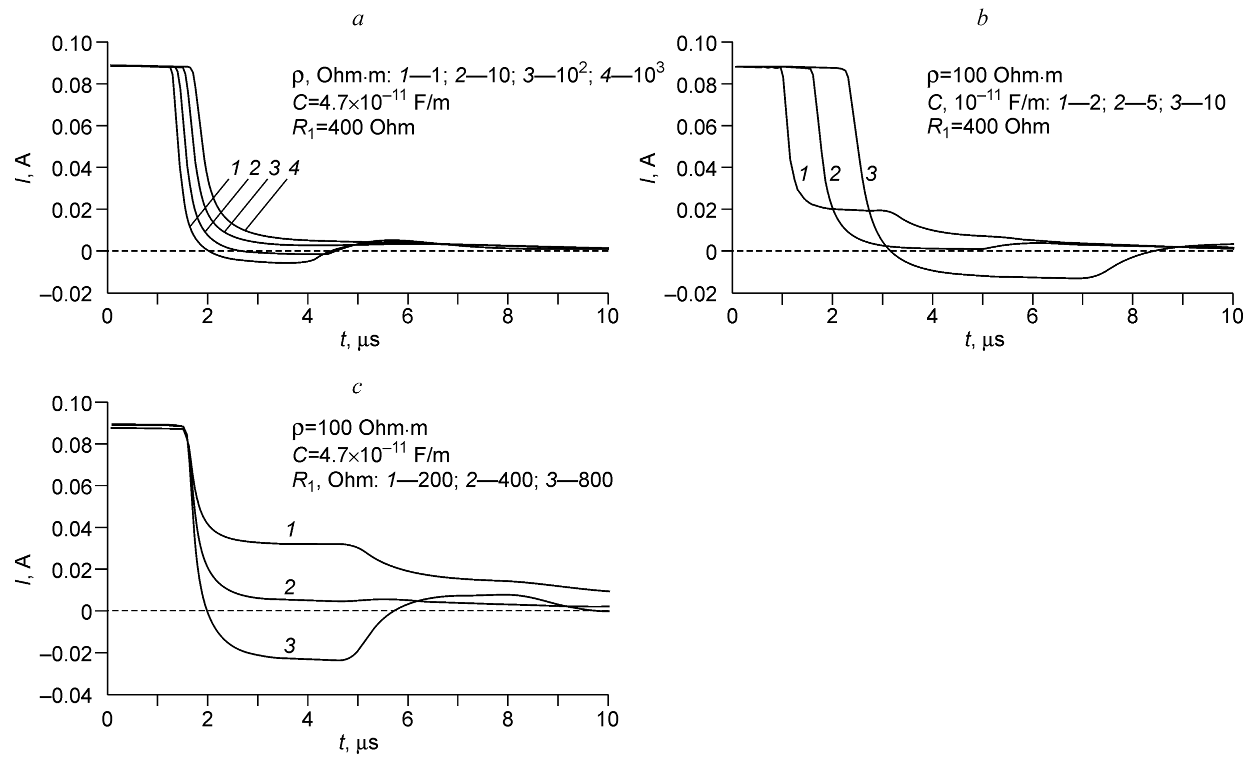

Fig. 6. Current turn-off waveforms at the midpoint ($x = 200$ m) of a 100×100 m loop as a function of earth resistivity (*a*), per unit length wire capacitance (*b*), and shunt resistance (*c*).

tions. At high frequencies and/or early times, the loop behaves as a symmetrical combination of two transmission lines formed by the wire and the earth under it. The parameters of the lines depend on frequency/time and local resistivity of the earth. This representation allows calculating the current at any time and at any loop point with reference to the theory of transmission lines. The solution is first obtained in the frequency domain and then converted to the time domain.

The per unit length resistance and inductance of the wire have to be estimated taking into account skin effect in the wire, interaction of each line with its own image current, and mutual inductance of the two lines.

Transient responses of a loop presented as a combination of two transmission lines can be inverted to estimate the line parameters and the earth resistivity at which the model turn-off current waveforms approach the observed ones. In this paper, as well as in earlier publications (Kozhevnikov, 2009, 2011), the earth below the loop has been approximated as a uniform conducting and/or polarizable halfspace. It is reasonable to expect that the use of other models, e.g., of a horizontally layered earth will improve the inversion quality.

Early-time transmitter self-responses depend on local resistivity and also on environment in some cases, which is inconsistent with the conventional "primary magnetic field" concept. Therefore, very early-time TEM response cannot be inverted using the theory and models of the conventional TEM method.

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References

Asten, M.W., 1987. Full transmitter waveform transient electromagnetic modeling and inversion for soundings over coal measures. Geophysics 52, 279–288.

Baskakov, S.I., 1980. Radio Circuits with Distributed Paameters [in Russian]. Vysshaya Shkola, Moscow.

Efimov, F.D., 1976. Transient self response of a receiver coil and its effect on loop–loop TEM measurements, in: Sedov, M.P. (Ed.), Geophysical Prospecting Methods. Resistivity Surveys [in Russian]. NPO Geofizika, Moscow, pp. 72–79.

Fitterman, D.V., Anderson, W.L., 1987. Effect of transmitter turn-off time on transient soundings. Geoexploration 24, 131–146.

Helwig, S.L., Kozhevnikov, N.O., 2003. Schwingungen in TEM Sendesignalen zu frühen Zeiten, in: Hördt, A., Stoll, J.B. (Eds.), 20 Kolloquium Elektromagnetische Tiefenforschung, Königstein, 29.09–03.10.2003, pp. 11–20.

Johnson, H.W., Graham, M., 1993. High-Speed Digital Design: A Handbook of Black Magic. Prentice-Hall, Englewood Cliffs, NJ.

Kozhevnikov, N.O., 2006. An ungrounded horizontal loop as a system with distributed parameters. Geofizika, No. 1, 29–39.

Kozhevnikov, N.O., 2009. Applying the transmission line theory to study ungrounded horizontal loop self-transients. Russian Geology and Geophysics (Geologiia i Geofizika) 50 (3), 222–233 (300–316).

Kozhevnikov, N.O., 2011. Damped current oscillations in a horizontal ungrounded loop and their correlation with ground water infiltration. Dokl. Earth Sci. 437 (2), 544–547.

Kozhevnikov, N., Helwig S., 2014. Very early time response of an ungrounded horizontal loop: theory and experiment, in: Extended Abstracts, 22nd EM Induction Workshop Weimar, Germany, August 24–30, 2014.

Kozhevnikov, N.O., Nikiforov, S.P., 1998. Distributed EM parameters of an ungrounded horizontal loop and their relation to the near-surface geoelectrical features, in: Proc. Symp. Application of Geophysics to Engineering and Environmental Problems, Chicago, USA. EEGS, Chicago, pp. 1019–1027.

Kozhevnikov, N.O., Nikiforov, S.P., 2000. Early time TEM response of an ungrounded horizontal loop—a new look, in: 62nd EAGE Conference, Expanded Abstracts. Glasgow, D-11.

Kozhevnikov, N.O., Plotnikov, A.E., 2004. TEM surveys for near-surface: Potentiality assessment. Geofizika, No. 6, 33–38.

Nikolaev, Yu.V., Sidorov, V.A., Tkachenko, A.K., 1988. Coincident-Loop Self Responses in TEM Soundings [in Russian]. Dep. VINITI 04.04.08, Moscow, No. 2563–V88.

Ott, H.W., 1976. Noise Reduction Techniques in Electronic Systems. John Wiley & Sons Canada, Limited, Technology & Engineering.

Plotnikov, A.E., 2014. Evaluation of limitations of the transient electromagnetic method in shallow-depth studies: numerical experiment. Russian Geology and Geophysics (Geologiya i Geofizika) 55 (7), 907–914 (1144–1152).

Qian, B., 1985. Selection of frequency bandwidth of a TEM receiving system to avoid false anomalies. Geoexploration 23, 519–526.

Raiche, A.P., 1984. The effect of ramp function turn-off on the TEM response of layered earth. Explor. Geophys. 15, 37–41.

Schamper, C., Esben, A., Kurt, S., 2014. Coil response inversion for very early time modelling of helicopter-borne time-domain electromagnetic data and mapping of near-surface geological layers. Geophys. Prosp. 62, 658–674.

Shalyt, G.M., 1982. Pulse Surveys for Flaw Detection in Power Lines [in Russian]. Energoizdat, Moscow.

Sharlov, M.V., Tatkov, I.G., Pospeev, A.V., 2010. Elimination of transient oscillation interfering with TEM response using the TEM processing software, in: Electromagnetic Methods. Proc. I Int. Conf. GEOBAIKAL_2010, Irkutsk. Irkutsk.

Simonyi, K., 1956. Theoretische Elektrotechnik. Deutscher Verlag der Wissenschaften, Berlin.

Sobolev, B.C., Shkarlett, Yu.M., 1967. Attachable and Screen Sensors (for Eddy Current Control) [in Russian]. Nauka, Novosibirsk.

Sokolov, V.P., Tabarovsky, L.A., Rabinovich, B.I., 1978. Transformation of TEM responses measured with current pulses of nonideal waveforms, in: Sokolov, V.P. (Ed.), Electromagnetic Fields in Exploration Geophysics: Theory and Practice [in Russian]. IGG SO RAN, Novosibirsk, pp. 81–92.

Vakhromeev, G.S., Kozhevnikov, N.O., Nikiforov, S.P., Nikitin, I.V., 1991. A Method of TEM Surveys. Patent No. 16995248. Published in Bull. Izobretenii, No. 44.

Vanchugov, V.A., Kozhevnikov, N.O., 1998. TEM surveys in the studies of the Nakyn kimberlite field (western Yakutia): Methods and results. Geologiya, Poiski i Razvedka Mestorozhdenii Rudnykh Poleznykh Iskopaemykh 22, 164–176.

Vishnyakov, A.E., Vishnyakova, K.A., 1974. Excitation and Measurement of Electromagnetic Fields in EM Exploration [in Russian]. Nedra, Leningrad.

Wang Yaw-Juen, Lui Shi-Jie, 2001. A review of methods for calculation of frequency-dependent impedance of overhead power transmission lines. Proc. Natl. Sci. Counc. ROC (A), 25 (6), 329–338.

Yu Cigong, Zhihong Fu1, Huaiqing Zhang, Heng-Ming Tai, Xuegui Zhu, 2014. Transient process and optimal design of receiver coil for small-loop transient electromagnetics. Geophys. Prosp. 62, 377–384.

Zakharkin, A.K., 1981. TEM Surveys with *TZIKL* Instruments: Methodological Guide [in Russian]. SNIIGGiMS, Novosibirsk.

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