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Time- and Frequency-Dependent Lightning Surge Characteristics of Grounding Electrodes

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***Abstract*—Two phenomena dominantly influence the dynamic performance of grounding electrodes during lightning discharge: 1) the time-dependent nonlinear behavior related to soil ionization during high-current pulses and 2) the frequency-dependent electromagnetic (EM) effects related to fast rise-time current pulses. The first phenomenon improves the grounding performance, while the second might have the opposite effect of impairing the grounding characteristics. It is important to simultaneously analyze these opposing effects; however, modern approaches that take into account both phenomena are mostly based on circuit theory, which does not allow for accurate analysis of fast rise-time pulses. This paper proposes a procedure that combines a rigorous EM approach based on the method of moments with an approximation method for assessing soil ionization effects as recently recommended by the CIGRE and IEEE Working Groups. Based on this procedure, we derive a simple new formula for approximating the surge characteristics that include time-dependent ionization and frequency-dependent inductive effects. We verify the model and formula by comparing our data with published experimental results. We also describe a parametric analysis of the opposing ionization and inductive effects.**

***Index Terms*—Frequency response, grounding, lightning, modeling, transient response.**

I. Introduction

VERTICAL and/or horizontal ground electrodes are often used for ground connections of electrical systems. These connections should have "sufficiently low impedance and current-carrying capacity to prevent buildup of voltages which may result in undue hazard to connected equipment and to persons" [1]. Ground electrode performance under normal and fault conditions is well understood [2]. However, the dynamic behavior of ground electrodes might be quite different during lightning discharge. Sensitivity analyses [3] have demonstrated the important influence of the magnitude of the tower footing impedance in power transmission-line lightning performance calculations. It is worth noting that voltage buildup at the grounding systems of transformers, poles, or lightning protective devices under the influence of a lightning return stroke is one of the main sources of overvoltages on the medium- and low-voltage installations [4].

Two different physical processes are considered to dominate the dynamic behavior of grounding electrodes during lightning discharge [5]. First, the nonlinear effects due to soil ionization might improve the grounding performance by lowering the grounding impedance during high current discharge by effectively enlarging the size of the electrode [6]. Second, the frequency-dependent inductive effects might impair the grounding performance by increasing the grounding impedance during fast rise-time lightning currents [7]. In the published literature, these phenomena have either been analyzed separately or the limitations of the chosen approaches have failed to offer more detailed insights into these mutually opposing effects.

Classical modeling approaches are based on circuit [8] or transmission-line theory [9]. Ionization effects around concentrated electrodes have been analyzed separately in many classical works (e.g., [10]–[13]). Frequency-dependent effects have also been analyzed separately, using the circuit approach (e.g., [14]–[16]), and the transmission-line approach (e.g., [17]–[19]). Combined approaches that account for both effects have all been based either on circuit theory (e.g., [20]–[22]) or on the transmission-line approach (e.g., [23]–[25]). In each case, grounding electrodes are represented by equivalent resistances, inductances, and capacitances, as derived from quasistatic analyses. The validity of these models is limited to a certain upper frequency [26], [27], which does not allow for the accurate analysis of fast rise-time lightning pulses with higher frequency content than the upper limit of the model frequency. This limitation is important since large overvoltages may be associated with fast rise–time currents [28].

More rigorous electromagnetic (EM) models have been introduced recently, based on the method of moments (MoM) [29]–[31] and on the finite-difference time-domain (FDTD) method [32]–[34]. FDTD methods are effective in transient analyses involving nonlinear and nonhomogeneous media, such as earth; however, since these methods require long computation times and significant memory, they are appropriate for rather small spaces [35]. MoM-based methods are effective in modeling thin-wire structures and can be used to model grounding effects in large telecommunication and power systems [31], [36]. They are suitable for high-frequency analysis, which allows for the accurate evaluation of very fast rise–time pulses, but they do not account for ionization effects.

Simple formulas that characterize the dynamic behavior of ground electrodes in the context of lightning currents are of great practical importance. However, simple formulas only take into account either frequency-dependent effects [37], [38], or nonlinear soil ionization effects [39].

This paper proposes a simple procedure to combine the rigorous MoM EM modeling approach [30], [31], with an approximate soil ionization effects formula as recommended by CIGRE

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[40] and IEEE Working Groups [41]. The motivation to use the MoM approach is that it produces the most accurate modeling of high-frequency phenomena in response to fast rise-time lightning current pulses. The recommended approximate soil ionization formula is derived from a significant base of experimental data, and is therefore a possible addition to the MoM approach. Use scenarios for the EM model and the recommended formula are further discussed in Section IV.

We derive a new simple formula for lightning surge characteristics that takes the nonlinear and frequency-dependent effects in the context of practical applications into account. This formula appears to be more versatile than other previously derived formulas. We compare the proposed procedure and the formula with a number of published experimental results [12], [13], [20], [42], [43], and we conclude that fairly good agreement exists.

This paper also presents a parametric analysis to further our understanding of grounding electrode behavior in the context of lightning currents. The complex interrelation of four parameters, namely, electrode length, soil ionization, current pulse front time, and intensity, is then analyzed to reveal the mutual importance of the possibly opposing soil ionization and frequency-dependent effects. To improve the accuracy of our fast rise-time pulse analyses, this study uses realistic lightning current pulse waveforms, which reproduce the observed concave rising behavior of typical recorded lightning current pulses. For simplicity, this paper is limited to the case of a single vertical or horizontal grounding electrode.

II. Surge Characteristics

The quantities used to characterize the dynamic behavior of the grounding electrode during lightning current pulses are defined elsewhere [24], [38]. For clarity, they are briefly summarized here.

We consider the current pulse $i(t)$ that is injected into the grounding electrodes and the resulting electric potential at the injection point in relation to the remote ground $v(t)$. $v(t)$ is often referred to as the transient ground potential rise. The impulse impedance Z is defined as

$$Z = \frac{V_m}{I_m} \tag{1}$$

where I_m and V_m are the peak values of $i(t)$ and $v(t)$, respectively. To compare the grounding performance under surge conditions with the performance at a power frequency, Z is related to the power frequency grounding resistance R through the dimensionless impulse coefficient A

$$A = \frac{Z}{R}. \tag{2}$$

Values of A larger than one indicate impaired surge performance compared to the low-frequency grounding performance, while values of A equal to or less than one indicate equivalent or superior surge performance, respectively.

For longer grounding electrodes, Z might become larger than R—that is, A might become larger than one. Consequently, the surge effective length ℓ_{eff} is defined as the maximal grounding electrode length for which A is equal to one [38].

The transient grounding impedance $z(t)$

$$z(t) = \frac{v(t)}{i(t)} \tag{3}$$

exhibits rapid variations during the initial surge period, after which it converges to the stationary condition characterized by a nearly constant $z(t)$ that can be approximated by the low-frequency grounding resistance R [25]. This is used to distinguish two periods of the transient response: 1) the initial surge or fast transient period and 2) the consequent stationary or slow transient period.

III. Approximate Procedure for Simultaneous Frequency and Time Analysis

In this section, we propose an approximate procedure that accounts for the frequency-dependent EM and time-dependent nonlinear soil ionization effects. To evaluate the surge characteristics (1)–(3), it is necessary to determine $v(t)$ for a given $i(t)$. The proposed procedure computes $v(t)$ in two steps

Step 1) The linear $v(t)$ is computed by taking into account only the frequency-dependent EM effects and ignoring the soil ionization effects.

Step 2) The soil ionization effects are taken into account as a function of the actual values of $i(t)$ in evaluating the total $v(t)$, including both frequency-dependent and nonlinear effects, over low- and high-current ranges.

Since the system is linear in the first step, a frequency-domain MoM EM approach [30], [31] is used to compute $v(t)$. This approach is based on an exact EM-field solution of an electric dipole in a conducting half space [44]. The EM model has been studied by many researchers during the last 20 years [26], [29], [30], and has been extensively verified by comparison with published experimental results (e.g., [31]). Its main advantage is its ability to accurately model EM interactions; however, its use is complex and requires dedicated computer software [45]. The motivation to use this approach here is based on a conclusion from a recent comparison with circuit and transmission-line models in [27] that even for the simplest vertical grounding electrode, the circuit and transmission-line models tend to overestimate the high-frequency inductive effects. A similar conclusion for more complex grounding arrangements was also demonstrated in [46]. However, the EM model does not take the soil ionization effects into account.

Bellaschi *et al.* [10] have determined the nonlinear relationship between the injected current and the grounding resistance of grounding electrodes and proposed that it may be linked to soil ionization at high currents. They concluded that soil ionization effectively increases the dimensions of the electrode, thus decreasing the grounding resistance. Based on the work of Korsuntcev [47] and Weck [48], the following formula for a nonlinear resistance $R(t)$ [Ω] as a function of the injected current $i(t)$ (in kikoamperes) was proposed and recommended by CIGRE [40], by an IEEE Working Group [41] and in an EPRI document [54]

$$R(t) = \frac{R}{\sqrt{1 + i(t)/I_g}}, \quad I_g = \frac{E_0 \rho}{2\pi R^2} \tag{4}$$

where ρ is the earth resistivity in ohms-meters, E_0 is the critical electric field intensity in kilovolts per meter, $E_0 = 300$ kV/m [40], and R represents the low-frequency low-current grounding resistance in ohms (1).

However, (4) disregards several important aspects of the phenomena, such as hysteresis [12] and surface sparking [49]. The rationale for neglecting these effects is that the more involved models, such as [12] and [49], require additional parameters of the soil that can be obtained in the laboratory, but are usually unmeasurable in practical scenarios. Furthermore, the neglect of surface sparking might be considered conservative, since this phenomenon would only improve the grounding performance [49]. An additional limitation of (4) is that the upper limit of the electrode length extends to about 30 m [41].

In the first step of the proposed procedure, the transient potential $v(t)$ is computed by the EM MoM model for a lightning current pulse $i(t)$, disregarding any soil ionization effects. We examine two terms of $v(t)$

$$v(t) = R \cdot i(t) + x(t) \tag{5}$$

where R is the power frequency grounding resistance. The first term on the right side of (5) approximates the linear resistive voltage drop in the ground, while the second term $x(t)$ is related to frequency-dependent phenomena and is mostly an approximation of the combination of the inductive and capacitive voltage drops. $x(t)$ is defined here as a reactive component of the voltage drop.

The second step of the proposed procedure is to determine the total high-current transient potential $v_i(t)$ that accounts for the soil ionization

$$v_i(t) = R(t) \cdot i(t) + x(t) \tag{6}$$

where $R(t)$ is computed from (4), and $x(t)$ is computed from (5). Since (4) is limited to electrodes with lengths of up to about 30 m, this is also a limitation associated with (6). Equation (6) approximates the soil ionization effect only in the context of the resistive part of the ground voltage drop, while its effect on the reactive voltage drop $x(t)$ is entirely ignored. Neglecting soil ionization effects in $x(t)$ exerts the most pronounced influence on the capacitive voltage drop, which results in a limitation of the use of (6). Consequently, (6) cannot be used when both capacitive and soil ionization effects are large, such as in the case of small electrodes in very resistive soil. This limitation is further discussed in Section V. The rationale for this omission is that soil ionization exerts a smaller effect on the inductive part of the soil voltage drop, which is of primary interest since the inductive effects might impair grounding performance, while the omission of the capacitive effects that improve the performance suggests a conservative approximation.

IV. Computation Test Cases

In the following sections, we analyze the influence of the dominant parameters on the dynamic behavior of grounding electrodes, simultaneously taking into account time- and frequency-dependent behavior.

The following cases are considered in our analysis, based on permutations of the following parameter values:

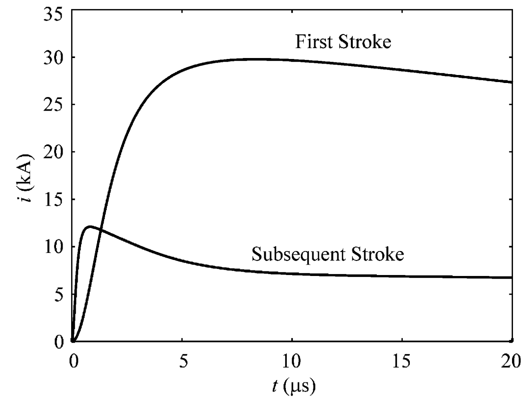

Fig. 1. First and subsequent return stroke currents.

- electrode length: 3 m for the case denoted "short electrode" in Figs. 2–7, and 30 m for a "long electrode;"
- resistivity of the earth: 30 Ωm for the case denoted "very conductive," 300 Ωm for "resistive," and 3000 Ωm for "very resistive;"
- lightning current waveforms: typical for the "first" and "subsequent" stroke (given later in this section).

The electrodes are horizontal copper conductors, with a diameter of 1.4 cm, and buried at a depth of 0.8 m in homogeneous earth. The earth has a relative permittivity of ten and a permeability equivalent to that of air. In all cases, the ionization critical electric-field intensity is $E_0 = 300$ kV/m [41].

Two lightning current waveforms corresponding to the typical first and subsequent return strokes, based on the observations of Berger *et al.* [50], are illustrated in Fig. 1. The current waveforms were selected by Rachidi *et al.* [51] to fit typical experimental data and are reproduced by means of a sum of Heidler's functions [52]. The reader is referred to [4], [38], or [41] for further detail on the functions used in our analysis.

The current pulses have the following characteristics:

- the first return stroke current pulse has a peak value of 30 kA, and a zero-to-peak time of about 8 μs, whereas
- the subsequent return stroke current has a peak value of 12 kA, and a zero-to-peak time of about 0.8 μs (Fig. 1).

Therefore, the first stroke is a rather slow rise-time, high intensity pulse, and the subsequent one is a fast rise-time, low intensity pulse. These waveforms appropriately reproduce the observed concave rising portion of the typical recorded lightning current pulses. We consider this approach preferable to other often-used waveforms that involve cosine or exponential functions and that are characterized by unrealistic convex wavefronts with a maximum current derivative at $t = 0$.

The lightning current pulses in all cases are injected at one end of the grounding electrode. Computations in the next section are for a horizontal electrode, but according to [38], the same general conclusions also apply for the case of two- or four-arm horizontal electrode arrangements, and to single vertical and multiple rod arrangements.

V. Influence of Parameters on Dynamic Performance

Figs. 2–7 show the dependence of the total potential relative to distant ground at the injection point and its resistive and

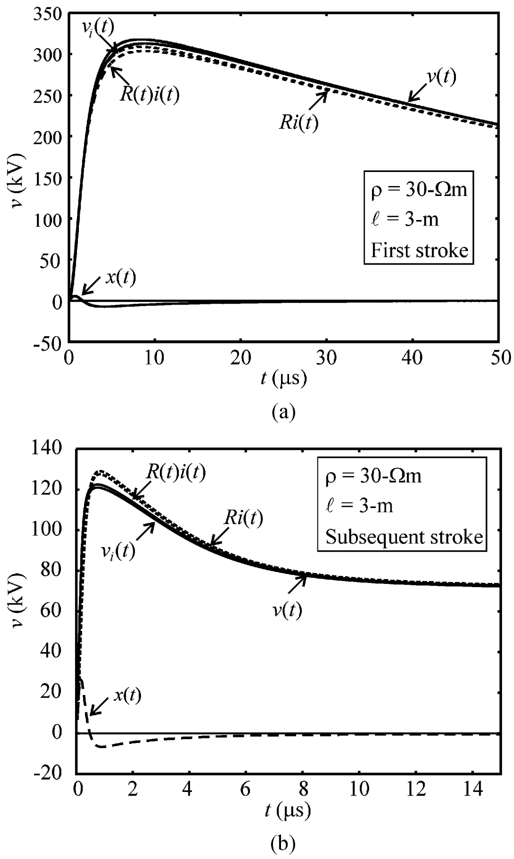

Fig. 2. Very conductive soil and short electrode.

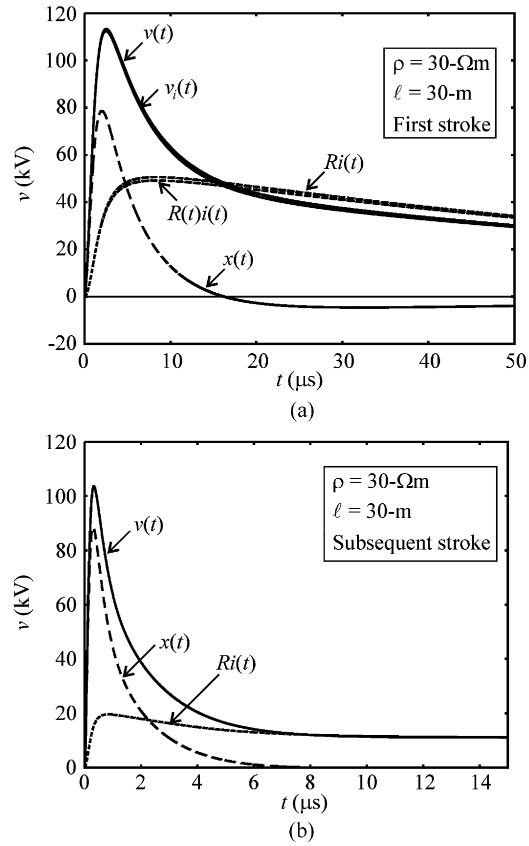

Fig. 3. Very conductive soil and long electrode.

reactive components as a response to the typical injected first and subsequent return stroke current pulses. Figs. 2 and 3 are examples of very conductive soil with a resistivity of 30 Ωm. Fig. 2 is for a short electrode with length $\ell = 3$ m; and Fig. 3 is for a longer electrode with length $\ell = 30$ m. Figs. 2(a) and 3(a) show responses of the typical first return stroke. Figs. 2(b) and 3(b) show responses of the typical subsequent return stroke. Figs. 4–7 are organized in a similar way, but Figs. 4 and 5 refer to more resistive soil with a resistivity of 300 Ωm, and Figs. 6 and 7 refer to very resistive soil with a resistivity of 3000 Ωm.

We examine two values for the potentials:

1) $v(t)$: when the ionization effects are ignored (5);
2) $v_i(t)$: when the ionization effects are taken into account (6) in the context of their resistive $Ri(t)$ or $R(t)i(t)$ and reactive $x(t)$ components.

   The difference between these potentials $v_i(t)$ and $v(t)$ is related to their resistive components. The first value features a linear resistive component $Ri(t)$ but ionization is ignored, while the second features a nonlinear ionization-relevant resistive component $R(t)i(t)$. The difference between these components represents soil ionization effects. Frequency-dependent effects are represented by the reactive component $x(t)$.

A. Duration of the Surge and Stationary Period

While soil ionization effects may last throughout the pulse duration, the frequency-dependent reactive effects last no more than several tens of microseconds during the initial surge. The

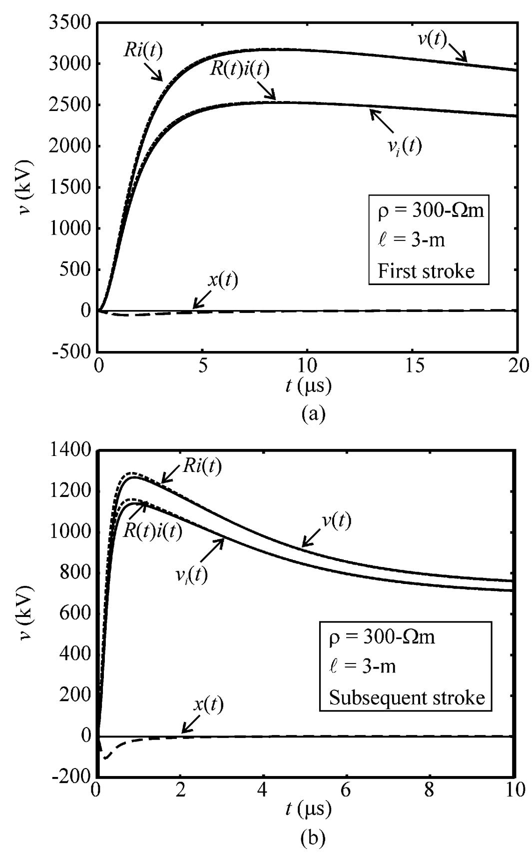

Fig. 4. Resistive soil and short electrode.

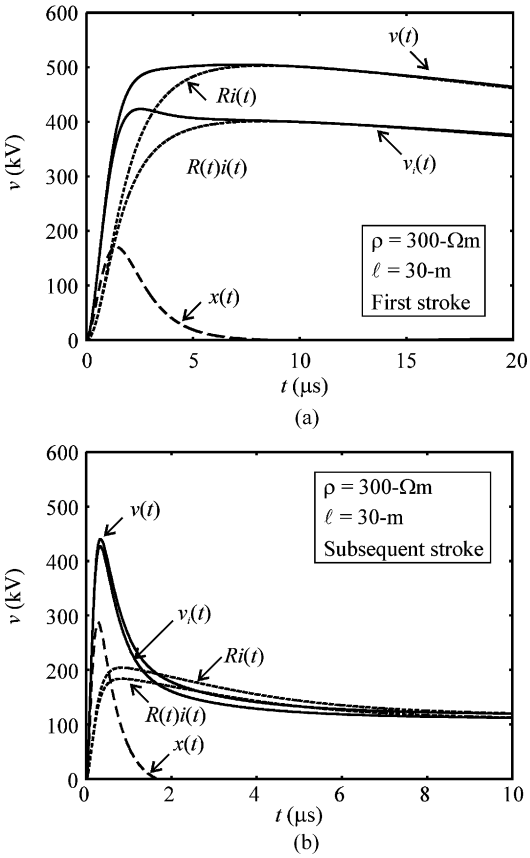

Fig. 5. Resistive soil and long electrode.

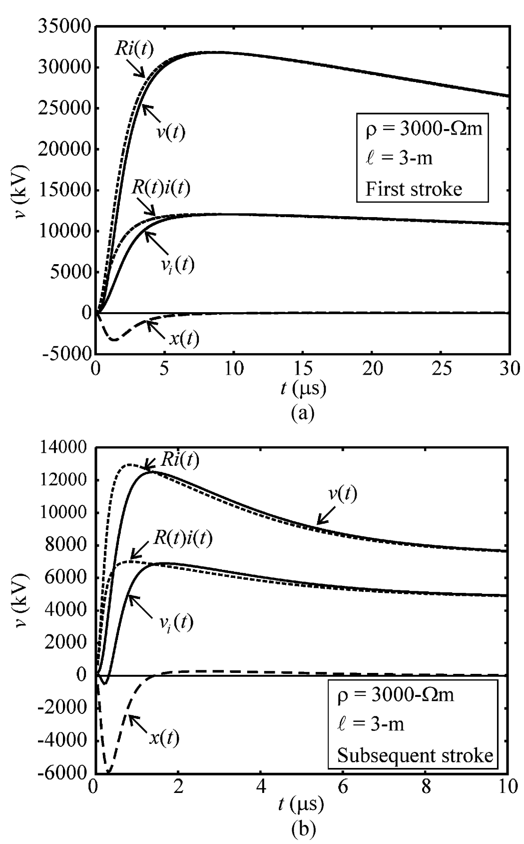

Fig. 6. Very resistive soil and short electrode.

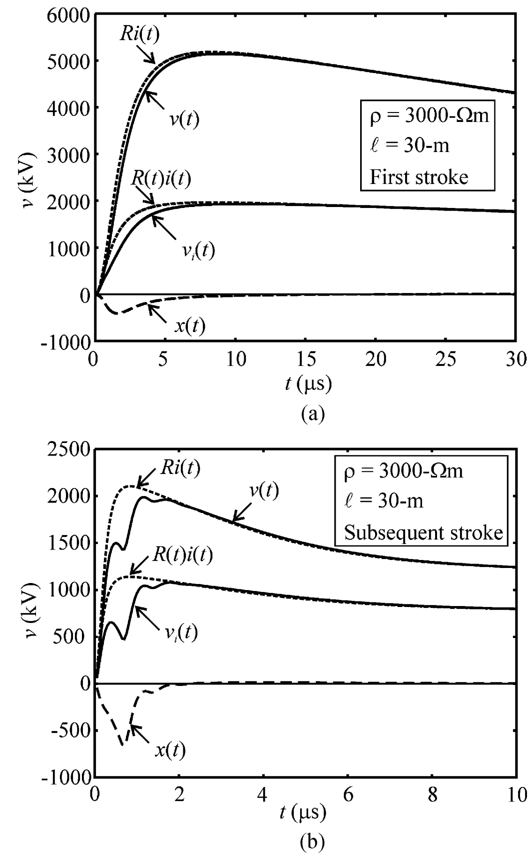

Fig. 7. Very resistive soil and long electrode.

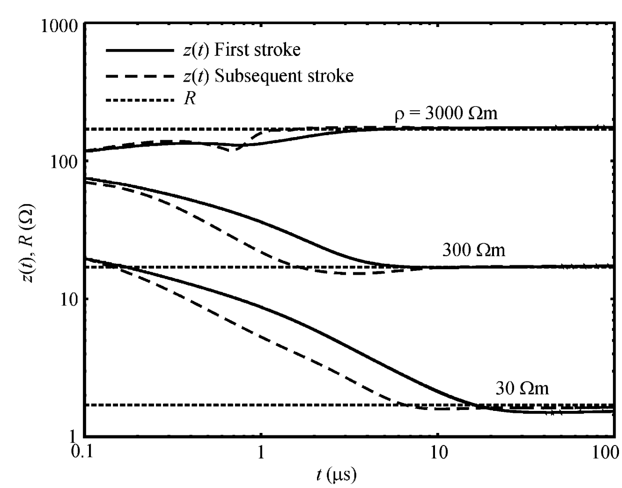

Fig. 8. Transient impedance $z(t)$ and power frequency resistance R for the 30-m-long electrode in Figs. 3, 5, and 7 (ionization is ignored).

limit between the surge and the stationary period can be approximated in Figs. 2–7 as the time when the reactive component $x(t)$ reaches zero.

This is also evident in Fig. 8 as the time when the transient grounding impedance $z(t)$ reaches the value of the power frequency resistivity R.

B. Influence of the Electrode Length

The dynamic behavior of short electrodes (3 m) is illustrated in Figs. 2, 4, and 6. We conclude that such electrodes, for all illustrated cases, can be adequately approximated by nonlinear resistance $R(t)$, such as (4). In very conductive soil, with a resistivity of about $30\,\Omega\mathrm{mm}$, only the linear resistivity R can be used. The reactive component is dominantly capacitive, and since it is small, it can be disregarded, except in very resistive soil and for fast rise-time pulses [Fig. 6(b)], for which rapid potential variations are filtered out during the rising portion of the pulse. However, the case in Fig. 6(b) illustrates the limits of the approximation when the soil ionization and capacitive effects are both large. The approximation ignores soil ionization effects in the context of the reduced capacitive voltage drop in the earth. This, in turn, leads to errors in the total voltage drop during the first few seconds of the pulse.

The behavior of longer electrodes (30 m in Figs. 3, 5, and 7) is more complex. The reactive behavior increases with fast rise-time pulses. It is dominantly inductive in very conductive soil and becomes dominantly capacitive in very resistive soil. The inductive voltage drop is much higher than the resistive one in very conductive soil during the surge period (Fig. 3). For more resistive soil and slower rise-time pulses [Fig. 5(a)], soil ionization effects nullify the inductive effects and improve grounding performance. In very resistive soil (Fig. 7), the soil ionization effects tend to dominate. In the case of fast rise-time pulses, the reflections of the voltage pulse from the other end of the grounding electrode during the rising portion of the pulse are shown [Fig. 7(b)]. This can be used to check the accuracy of the computations. In this case, the speed of wave propagation along the electrode ν is not affected by the soil resistivity and may be determined by

$$\nu = 1/\sqrt{10\varepsilon_0\mu_0} \approx 0.3c \tag{7}$$

where c is the speed of light. The arrival of the reflected wave from the other end of the electrode to the feed point can be computed from $\tau = 2 \times 30/\nu = 0.66\ \mu$s, which is in agreement with the results in Fig. 7(b).

C. Influence of Soil Resistivity

The resistive behavior is dominant throughout the pulse in very conductive soil and for small electrodes (Fig. 2), while inductive behavior becomes dominant during the surge period for longer electrodes, especially in the case of fast rise-time pulses (Fig. 3). For example, in Fig. 3(b), the peak values of the inductive voltage drop are four times larger than the resistive one. In more resistive soil for long electrodes, especially for slower rise-time pulses and larger currents, the opposite effects of soil ionization overcome the inductive effects, for example, in Fig. 5(a). In very resistive soil, ionization effects remain dominant. In this case, the capacitive behavior filters out fast variations of $v(t)$ during the rising portion of the pulse (Figs. 6 and 7).

D. Influence of the Current Pulse Front

Fast rise-time pulses largely emphasize reactive effects during the surge period, especially in the case of long electrodes [Figs. 3(b), 5(b), and 7(b)].

E. Influence of the Current Pulse Intensity

High intensity currents cause ionization when the electric field at the electrode surfaces exceeds E_0. This effect is visible in all analyzed cases except for very conductive soil. This effect improves the grounding performance throughout the duration of the pulses and is more pronounced in more resistive soil.

VI. Simple Formula for the Impulse Coefficient

New formulas for the lightning surge characteristics of grounding electrodes have recently been proposed [38]. These formulas are applicable for a conservative analysis, that is, when the influence of the ionization and capacitive behavior is ignored. In these cases, the impulse coefficient A (2) may be either equal to one, due to resistive behavior, or larger than one due to inductive behavior.

In this paper, we extend the formula for the impulse coefficient to account for ionization effects, based on the method introduced in Section III. Following the approximate procedure in Section III, the impulse coefficient A is first determined by ignoring ionization, and then the effects of ionization are separately taken into account.

The first step is to compute the coefficients α and β [38]:

$$\alpha = 0.025 + \exp\left(-0.82 \cdot (\rho \cdot T_1)^{0.257}\right) \tag{8a}$$
$$\beta = 0.17 + \exp\left(-0.22 \cdot (\rho \cdot T_1)^{0.555}\right). \tag{8b}$$

Here, the soil resistivity ρ is in ohm-meters, and current pulse zero-to-peak time T_1 is in microseconds. Coefficients α and β do not have any physical meaning; they are deduced from computer simulations by using the EM model [38].

Next, the effective length ℓ_{eff} (in meters) is determined by

$$\ell_{\mathrm{eff}} = \frac{1-\beta}{\alpha}. \tag{9}$$

When the length of the grounding electrode ℓ (in meters) is less than or equal to ℓ_{eff}, the impulse coefficient is equal to one

$$A = 1, \quad (\ell \le \ell_{\mathrm{eff}}). \tag{10}$$

For the electrode length $\ell \ge \ell_{\mathrm{eff}}$, the dependence of the impulse coefficient A on ℓ is nearly linear and may be approximated by

$$A = \alpha\ell + \beta, \quad (\ell \ge \ell_{\mathrm{eff}}). \tag{11}$$

To take into account the effects of ionization, we apply (4). The modified impulse coefficient A_i that takes into account the frequency-dependent inductive and time-dependent nonlinear behavior is determined by

$$A_i = \frac{1}{\sqrt{1 + I_m/I_g}} + A - 1 \tag{12}$$

where I_m is the current pulse peak value (in kiloamperes), I_g is computed by (4), and A is computed by using (10) or (11).

TABLE I
INPUT PARAMETERS OF THE PROPOSED FORMULA (12)

Parameter	Symbol	Unit	Validity range
Electrode length	ℓ	m	3 – 30
Soil resistivity	ρ	Ωm	10 – 1000
Current pulse zero-to-peak time	T_1	μs	0.2 – 10
Current pulse peak value	I_m	kA	0 – 100
Soil's critical E field	E_0	kV/m	300 – 1000

Next, the impulse impedance Z_i in ohms and the peak value of the transient ground potential rise V_{mi} in kilovolts may be determined, respectively, from

$$Z_i = R \cdot A_i \tag{13}$$

$$V_{mi} = Z_i \cdot I_m. \tag{14}$$

The list of input parameters and their validity ranges for the proposed formula (12) is given in Table I.

One interpretation of the values of A_i (12) is:

$A_i < 1$ grounding performance is improved due to ionization (dominant nonlinear resistive behavior);

$A_i = 1$ grounding performance is identical to power frequency performance (linear resistive behavior);

$A_i > 1$ grounding performance is impaired due to inductive effects (dominant inductive behavior).

These formulas disregard capacitive effects; however, this may be considered a safe and conservative approach since capacitive behavior improves grounding performance by reducing $v_i(t)$ [25].

Simple formulas in this section are applicable in case of vertical and horizontal electrodes. They also can be used for two- and four-arm horizontal arrangements and for single-, two-, and four-driven rod arrangements by using reduction factors given in [38, Table III].

VII. OTHER FORMULAS FOR THE IMPULSE COEFFICIENT

One previously developed formula for the impulse coefficient is [37]

$$A = \exp\left(0.333 \cdot (\ell/\ell_{\text{eff}})^{2.3}\right), \quad \ell_{\text{eff}} = 1.4\sqrt{\rho T_1}. \tag{15}$$

Another formula for the impulse coefficient of a linear horizontal conductor is developed in [39]

$$A = 1.62 \cdot \rho^{-0.4}(0.5 + \sqrt{\ell}) \cdot \left[0.79 - \exp\left(-2.3 I_m^{-0.2}\right)\right]. \tag{16}$$

Formula (15) takes into account only the frequency-dependent inductive effects and ignores soil ionization. Formula (16) ignores T_1, which is crucial for the frequency-dependent effects and it therefore also ignores frequency-dependent inductive effects.

TABLE II
EXPERIMENTAL ELECTRODE AND SOIL PARAMETERS

Case	Electrode	Soil	Publication
Fig. 9	Vertical ℓ = 1 m a = 25 mm	ρ = 42 Ωm ε_r = 10 E_0 = 300 kV/m	Geri [20, Fig 12]
Fig. 10	Horizontal ℓ = 5 m a = 4 mm h = 0.6 m	ρ = 42 Ωm ε_r = 10 E_0 = 300 kV/m	Geri [20, Fig 14]
Fig. 11	Vertical ℓ = 1.5 m a = 7 mm	A: ρ = 160 Ωm F: ρ = 450 Ωm G: ρ = 1070 Ωm E_0 = 300 kV/m	Sekioka et al. [42, Fig. 7b]
Fig. 12	Vertical ℓ = 2.5 m a = 8 mm	ρ = 100, 500, 1000, 3000 Ωm E_0 = 300 kV/m	Mousa [53, Fig. 7]
Fig. 13	Vertical ℓ = 2.5–10 m	ρ = 20 – 2000 Ωm E_0 = 300 kV/m	Ryabkova et al. [13]; Liew et al. [12, Fig. 13]; He et al. [39]; Mousa [53, Fig. 7]
Fig. 14	Horizontal ℓ = 8 m a = 6 mm h = 0.6 m	ρ = 65 Ωm ε_r = 15	H. Rochereau et al. [43]

Here: ℓ is the length, a is the radius, and h is the depth of burial.

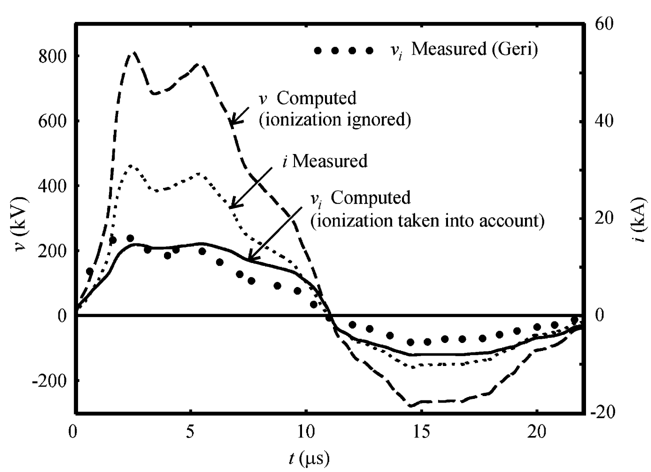

Fig. 9. Comparison with measured transient potentials of a vertical electrode.

VIII. COMPARISON WITH EXPERIMENTAL DATA

To determine the accuracy and applicability of our proposed method, in this section, we compare the simulation results with published experimental data as a reference. The values of the basic parameters of the experimental cases are given in Table II and comparisons between the simulation and experimental results are given in Figs. 9–13.

In Figs. 9 and 10, we compare the results of the proposed approximation described in Section III. The reference case is from Geri [20, Figs. 12 and 14]. For a given electrode current pulse i, the potential at the injection point v is computed when

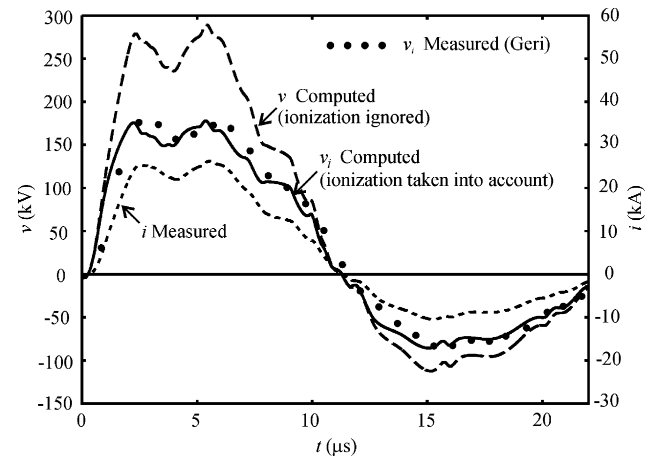

Fig. 10. Comparison with measured transient potentials of a horizontal electrode.

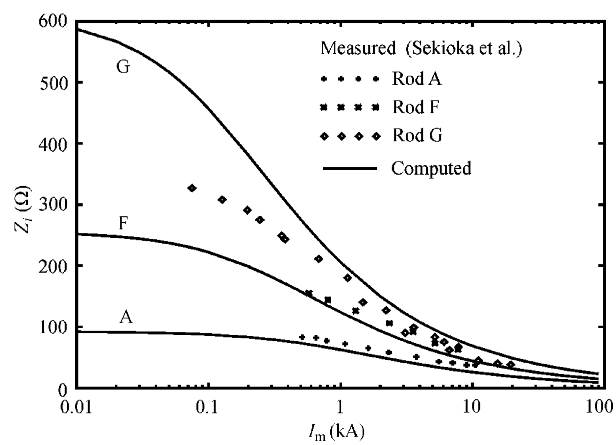

Fig. 11. Comparison with measured impulse impedance.

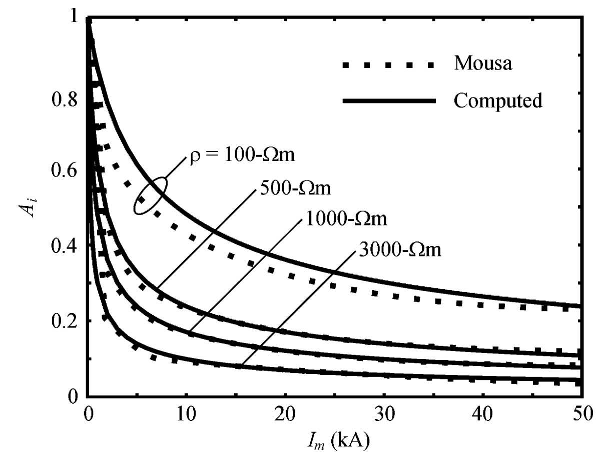

Fig. 12. Comparison with measured impulse coefficient.

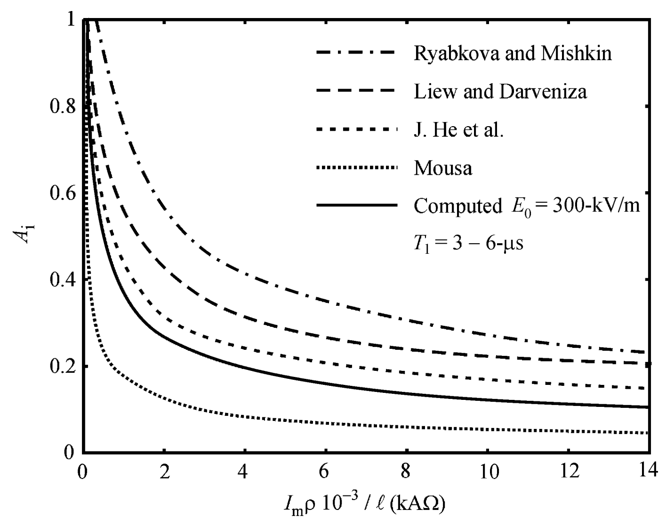

Fig. 13. Comparison with a measured impulse coefficient from four research groups.

ionization is ignored by using (5), and v_i is calculated when the ionization is accounted for by using (6). An acceptable level of agreement between the simulation and experimental results is confirmed for a vertical electrode in Fig. 9 and for a horizontal electrode in Fig. 10.

In Fig. 11, we examine the proposed simple formula in the context of the impulse impedance Z_i (13). The reference case is from Sekioka's *et al.* [42, Fig. 7(b)]. Experimental results refer to the impulse impedance of a driven rod in soil with three different values of resistivity (Table II). The rise times of the injected current pulses are about 2 μs and the peak values reach as high as 40 kA. Results using our simple formula are generally consistent with the experimental data, except for the low current values in the case of "Rod G" (Fig. 11). The "Rod G" differences might be linked to the neglected capacitive effects in (10) and (12).

In Fig. 12, we compare the computation of the impulse coefficient A_i (12) with measured data from Mousa [53, Fig. 7] for the case of a single vertical electrode under high current discharge conditions. Computations using (8)–(12) are mostly consistent with Mousa's results, as shown in Fig. 12.

In Fig. 13, we compare the proposed formula for A_i (12) with published experimental results from four different research groups. Ryabkova and Mishkin in [13] introduced a normalizing ratio $I_m\rho/\ell$ for the case of a single vertical electrode. They presented the variation of the impulse coefficient A_i as a function of the mentioned normalizing ratio based on a comprehensive set of measurements. Fig. 13 shows their generalized curve (a median line of scattered results). Liew and Darveniza in [12, Fig. 13] also predicted impulse characteristics of a single rod. For the purpose of comparison, the median values of their results have been normalized in a similar fashion to Ryabkova and Mishkin results and also plotted in Fig. 13. Also in Fig. 13, we plot the median line of the results by J. He *et al.* [39] by using (16) for the same parameter ranges. Formula (16) is an empirical regression analysis formula derived from a large set of experimental data [39]. Finally, results from Mousa [53, Fig. 7] are also plotted in this figure. There is a general agreement in the trends between the various experimental results; however, the four research groups have estimated the extent of improvements in grounding performance differently due to soil ionization. One explanation of these differences might be in the use of different methods; for example, Ryabkova and Mishkin cite results from laboratory experiments by using small-scale models. However, it is more important to note that Fig. 13 shows that

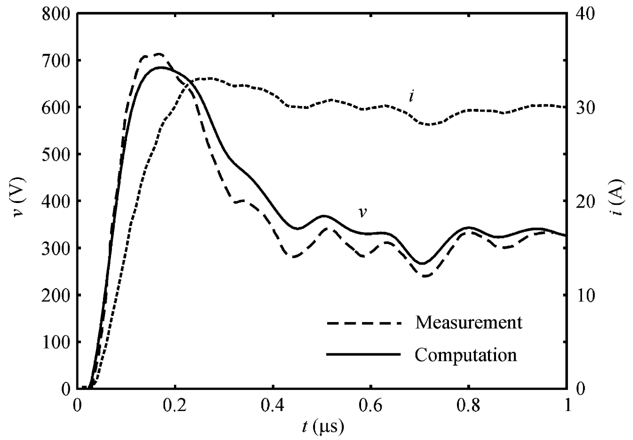

Fig. 14. Comparison with measurements from Electricité de France.

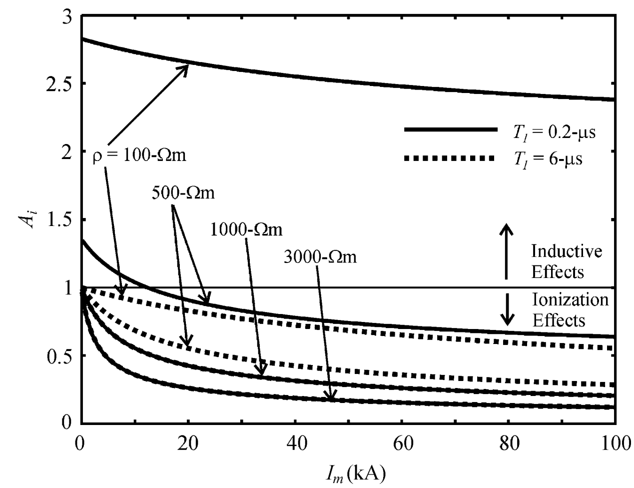

Fig. 15. Impulse coefficient A_i for current pulses with front times $T_1 = 0.2\ \mu$s and $T_1 = 6\ \mu$s in case of a single rod (12 m long, 16-mm diameter, $E_c = 300$ kV/m).

there is not "one referent generalized curve" that can be extracted from the published experimental results. Ionization is an irregular nonlinear process in nonhomogeneous soil that features electrical properties that change with weather conditions, temperature, moisture, and so on. Typically, even the same physical grounding electrode might perform differently under different circumstances. In addition, it is evident from Fig. 13 that the more recent investigations, including those of He *et al.* [39] and Mousa [53], estimate greater reductions in grounding resistance with high intensity currents than the earlier publications by Ryabkova and Mishkin [13] and by Lew and Darveniza [11].

To compare (12) with these published experimental results, the computed results are also presented with a median line in Fig. 13. The trend in the computed results from (12) is consistent with recent investigations; with larger disparity with Mousa's results [53] and better agreement with He *et al.*'s results [39] (Fig. 13).

We note that Fig. 13 presents median lines of five sets of overlapping scattered results for a range of parameters given in Table II only to suggest a general idea of the differences in the results from different approaches.

All results in Figs. 9–13 are for rather slow rise-time current pulses with front times that last a few microseconds and these data consequently show mostly the effects of soil ionization. Faster rise-time current pulses are necessary for inductive effects to occur. Some of the rare carefully performed and well-documented experiments with fast rise-time currents were carried out by Electricité de France, for example, [28] and [43]—although these involve only low intensity current pulses. Fig. 14 shows these measured results for a current pulse i (dotted line) with a zero-to-peak time of about 0.2 μs injected in a grounding electrode together with the potential relative to remote ground at the injection point v (broken line) [43]. Since there are no ionization effects for such low intensity currents, v is computed by (4) (solid line). The computed results are consistent with measurements.

The measured voltage peak in Fig. 14 is about 720 V and the current peak value is about 33 A. Therefore, the measured impulse impedance Z is 22 Ω. The large voltage peak and the fact that the voltage pulse leads the current pulse indicate inductive behavior. The power frequency grounding resistance is about $R = 10\ \Omega$ and, consequently, the measured $A = 2.2$. Equation (12) leads to $A = 2.4$, while (15) leads to $A = 2.6$.

Unfortunately, published experimental results that simultaneously demonstrate opposing soil ionization and inductive effects could not be found. Therefore, the approximate procedure involving (6) and (12) could be verified only for cases when either soil ionization or inductive effects are dominant.

IX. Simultaneous Analysis of Soil Ionization and Inductive Effects

Neither of the aforementioned impulse coefficient formulas (15) [37] and (16) [39] are suitable for the simultaneous analysis of the mutually opposing inductive and soil ionization effects. Equation (15) only takes the inductive effects into account and (16) only takes the soil ionization effects into account. However, the new formula (12) can be used to approximate the ranges of parameters where both opposing effects may be important.

As an example, Fig. 15 shows the impulse coefficient A_i computed by (12) in case of a single rod (12 m long, 16-mm diameter) subjected to the "slow-rise time" ($T_1 = 6\ \mu$s) and "fast-rise time" ($T_1 = 0.2\ \mu$s) current pulse in soil with different resistivity. It is clear that for the "slow-rise-time" current pulses, the ionization effects are dominant in all cases. Inductive effects are dominant for the "fast-rise-time" current pulses only for relatively low resistivity soil ($\rho = 100\ \Omega$m), while for more resistive soil ($\rho = 500\ \Omega$m), the soil ionization and inductive effects nullify each other. For highly resistive soil ($\rho =$ 1000- and 3000-Ωm) ionization effects are dominant even for the "fast-rise-time" current pulses.

X. Conclusion

Simultaneous analysis of the ionization and inductive effects is as follows.

1) The dynamic behavior during lightning current pulses has distinct characteristics in the initial surge period and in the subsequent stationary period. The duration of the surge period lasts no longer than a few tens of microseconds, and the stationary period continues until the end of the pulse.

2) The grounding electrode performance may deteriorate due to frequency-dependent inductive phenomena, but only during the surge period. This effect is enhanced by fast rise-time current pulses, highly conductive soil, and electrode length.
3) The grounding electrode performance may be improved by soil ionization phenomena during the entire transient response. This effect occurs for current values for which the electric field at the surface of the electrode exceeds the critical soil value. It depends on current intensity, soil resistivity, and the critical electric-field value.
4) In very resistive soil, the capacitive effects also improve the grounding performance by effectively filtering out rapidly varying voltages during the surge period.
5) Cases exist when either ionization or inductive effects are dominant and the other effect can be neglected, but there are also important cases when inductive and soil ionization effects are simultaneously important. Since they nullify each other, it is important to consider both in the analysis of the optimal form and dimension of grounding electrode arrangements.
6) The accuracy and applicability of the proposed procedure for simultaneous analysis of inductive and soil ionization effects and the formula for calculating impulse coefficient were shown to be consistent with a number of published experimental results.

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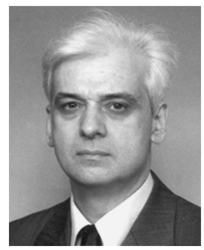

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