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Lightning Surge Efficiency of Grounding Grids

Leonid Grcev, *Senior Member, IEEE*

***Abstract*—Two phenomena are important in the dynamic behaviors of grounding systems: soil ionization and inductive behavior. This paper solely focuses on the inductive effects that might impair dynamic performance. This is in agreement with conclusions of recent investigations that the effect of soil ionization can be ignored for grounding grids in high-voltage substations. The inductive effects are enhanced by fast front current pulses that have high-frequency content. We improve the analysis by applying a rigorous electromagnetic model and a realistic waveform of lightning current pulses. The new computer simulation results suggest that values of the grounding grid impulse coefficient are nearly linearly dependent on the side length of square grids. We derive new empirical formulas that approximate the impulse impedance, impulse coefficient, and effective area of grounding grids. These new formulas enable identification of parameters for which the surge performance of grounding grids might be significantly impaired in comparison to low-frequency performance. We verify the simulation method used for deriving the new formulas by comparing our data with published experimental results.**

***Index Terms*—Electromagnetic analysis, grounding, lightning, modeling, transient response.**

NOMENCLATURE

i, I_m	Injected lightning current pulse into the grounding grid and its peak value (in amperes).
v, V_m	Electric potential pulse at feed point in relation to remote ground and its peak value (in volts).
T_1	Lightning current pulse zero-to-peak time (in microseconds).
R	Power frequency grounding resistance of the grid (in ohms).
Z	Impulse impedance of the grid (in ohms).
A	Impulse coefficient.
a, s	Square grid-side length and conductor spacing (in meters).
a_{eff}	Side length of the effective area of a square grid (in meters).
ρ	Soil resistivity (in ohms-meters).
ε_r	Relative soil permittivity.

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I. INTRODUCTION

THE efficiency of grounding systems to discharge currents into the earth under surge conditions determines the level of protection they provide against the effects of lightning. It is well known that when fast front lightning current pulses are injected in grounding systems, because of the limited velocity of pulse propagation along the ground electrodes, the initial current is discharged into the earth through a relatively small area of the grounding system around the feed point [1]–[3]. The area enlarges as the current spreads over the grounding system and encompasses the whole grounding system after several microseconds [4]. Two periods can be distinguished: 1) the initial surge period (before the pulse reaches the end of the grounding system) and 2) the latter stationary period (after the pulse has reached the end of the grounding system). The initial surge period is characterized by a large and uneven distribution of conductor potentials; the latter stationary period is characterized by the current discharged into earth through the whole grounding system with an even distribution of potentials that is typical for low-frequency regimes. Large currents and uneven potentials in small areas around the feed point during the initial surge period could cause danger to people and equipment [5]. There is a massive body of literature describing the performance of grounding systems under lightning currents. The reader is referred to the reference sections of earlier papers by the author [6]–[8] for useful information on recent work in the same subject.

The behavior of grounding grids under lightning surge conditions has been thoroughly analyzed by Gupta and Thapar [9]. To characterize the surge behavior of grounding systems, they used impulse impedance

$$Z = \frac{V_m}{I_m}. \quad (1)$$

To compare the grounding performance under surge conditions with the performance at the power frequency, Z is related to the power frequency grounding resistance R through the impulse coefficient

$$A = \frac{Z}{R}. \quad (2)$$

Gupta and Thapar analyzed the influence of several parameters on Z, including soil resistivity, dimension of the square grounding grid, position of the current injection point, and current-pulse front time [9]. They also introduced an effective area of grids as a limiting grid dimension, for which further increases of value do not result in any appreciable change in Z. Based on the results of computer simulations, they provided empirical formulas for the effective area and the impulse coefficient. One important conclusion in [9] was that the effects of soil ionization on the impulse impedance can be ignored for grounding grids.

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All of the conclusions of Gupta and Thapar [9] were repeated recently in another study [10]. However, fast front lightning current pulses raise two issues that might restrict the accuracy of the methods applied in [9] and [10].

First, the analysis in [9] and [10] is based on circuit theory models, wherein an underlying quasistatic approximation constrains the validity to some upper frequency limit. Olsen *et al.* have proposed in [11] that this upper frequency limit can be determined from a requirement where the length of the grounding electrode represented by a circuit model should be less than one-tenth of the wavelength in the medium. This limitation generally restricts the accuracy of the analysis of responses to fast front lightning current pulses that have high-frequency content (e.g., subsequent return strokes). This limitation has been discussed in [12] for vertical ground rods and in [13] for horizontal wires. It has been also pointed out in [14] that such an upper frequency limit for circuit models might be even lower in complex grounding arrangements, such as grounding grids.

Second, [9] and [10] use an unrealistic approximation of the convex front and a maximum current derivative at $t = 0$ of a lightning current pulse (i.e., a cosine function in [9] and an exponential function in [10]). The realistic modeling of the front is important for computations of inductive effects, which occur during the initial rise of the lightning current pulses. Recent additions to the literature related to grounding grids [15], [16] are also constrained by the circuit theory models and the quasistatic approximation.

More recently, newly introduced rigorous models based on the electromagnetic-field theory have overcome the limitations of the circuit models and quasistatic approximation (e.g., [17]–[19]). These models, therefore, might be better suited for modeling the responses to high frequencies and faster-rising lightning current pulses.

In earlier papers [6], [7], the author presented the results of analytical investigations and empirical formulas to evaluate impulse impedance and the impulse coefficient of simple arrangements of grounding electrodes. The goal of this paper is to extend these investigations to complex arrangements of grounding electrodes, such as the square grounding grids.

In this paper, we use the same approach to improve the analysis as in the earlier papers [6], [7]. First, the electromagnetic model described in [17] is applied. One motivation to use this model is that it is based on a very accurate numerical method developed from the antenna theory (i.e., the method of moments [20] that is suitable for high-frequency analysis). Furthermore, it is based on an exact mathematical model (i.e., the exact solution of the electromagnetic fields of an electric dipole in the earth [21], similar to the approach used by Burke *et al.* [22]). Olsen *et al.* [11, p. 1081] have established this approach as an "exact" solution to this problem and as a "gold standard" for comparisons. We use the corresponding computer model [23] that is recommended in the International Council on Large Electric Systems (CIGRÉ) document [5, p. 97]. Notably, the computer model's accuracy has been thoroughly validated through comparisons with published experimental results by a number of independent research groups (see [4], [7], and [24]). Second, realistic lightning current-pulse waveforms [25] are used to reproduce the observed concave rising portion of recorded lightning current pulses [26]. Finally, we compare the simulation method with published experimental results [33], and we conclude that a fairly solid agreement exists.

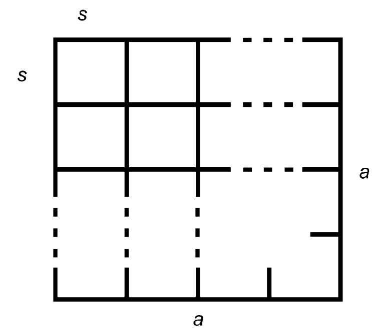

Fig. 1. Square grid chosen for computations.

This paper proposes new general curves and empirical formulas for the impulse coefficient and the effective area of grounding grids. These have been derived from computer simulations on a large number of test cases for parameters in the ranges of interest for practical scenarios (i.e., ground resistivity 10–1000 Ωm, square grid side size 5–100 m, conductor separation 5–10 m, position of the current injection in the center and corner points, and lightning current pulse zero-to-peak-time 0.8–8 μs).

The effects of soil ionization are disregarded in the new formulas, which is in agreement with the conclusions in recent investigations [9], [10] that suggest that the effect of soil ionization is likely to be small and can be ignored for grounding grids in high voltage substations.

II. Computation Test Cases

We consider a square ground grid with side lengths a in a range from 5 to 100 m, as shown in Fig. 1. The grid is composed of square meshes with the spacing between conductors s equal to 5 or 10 m. The conductors are constructed from copper with a 7-mm radius. The grid is buried at a depth of 0.8 m in uniform soil with ρ ranging from 10 to 1000 Ωm, and $\varepsilon_r = 10$.

In this study, we use two lightning current waveforms corresponding to the first and subsequent return strokes suggested in the CIGRÉ document [27]. The current waveforms are chosen based on Rachidi *et al.* [25] to fit experimental data based on observations of Berger *et al.* [26] as shown in Fig. 2:

- the first return stroke current pulse has a peak value of $I_m = 30$ kA, a zero-to-peak time of about $T_1 = 8$ μs and a maximum steepness of 12 kA/μs, where
- the subsequent return stroke current has $I_m = 12$ kA, $T_1 = 0.8$ μs and a maximum steepness of 40 kA /μs.

Two scenarios for the position of the strike points are considered: one in the middle point of the grid and another in the corner.

III. Typical Dynamic Behavior

The typical dynamic behavior of grounding grids is analyzed in detail elsewhere (e.g., [9], [14], [28], [29]). In this section, we briefly review characteristics of the inductive behavior that might impair the grounding performance in the first moments of the lightning strike.

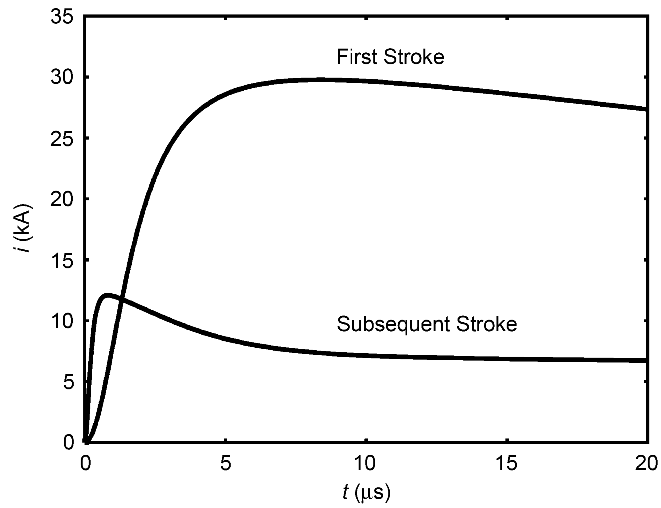

Fig. 2. Approximation of the first and subsequent return stroke currents.

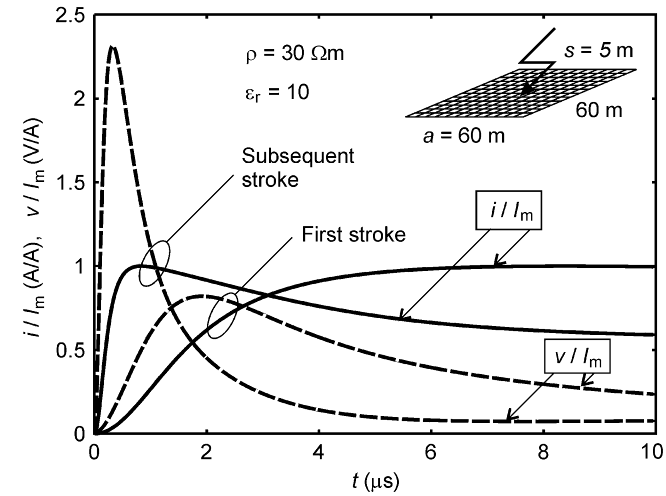

Fig. 4. Grounding grid dynamic behavior for first and subsequent return stroke current pulse waveforms (Fig. 2) and strike point in the middle point of the grid.

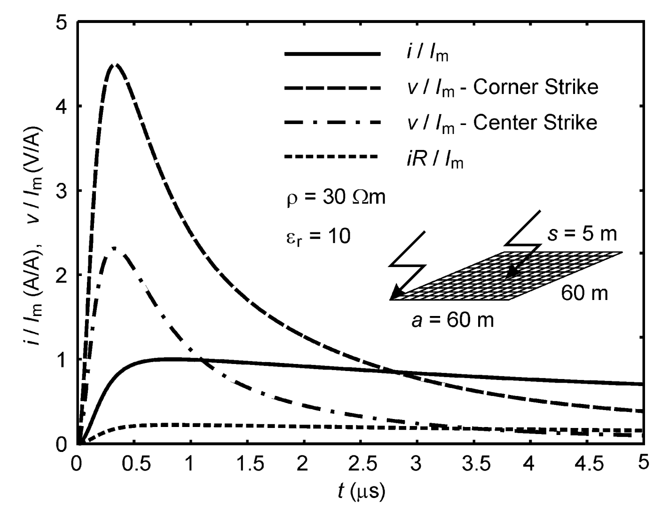

Fig. 3. Grounding grid dynamic behavior in the case of alternative strike points at the middle and at the corner point for subsequent return stroke current-pulse waveform (Fig. 2).

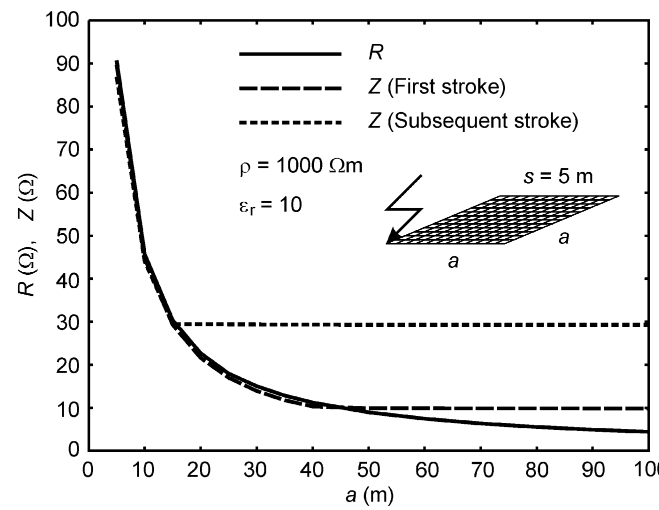

Fig. 5. Dependence of the impulse impedance and low-frequency resistance on the grid size.

Fig. 3 shows one example of a typical dynamic behavior of a grounding grid. The grid is hit by a lightning current pulse i with a waveform related to a subsequent stroke (Fig. 2). The considered grid has a 60×60 m^2 surface and a 5×5 m^2 mesh and is buried in soil with 30-Ωm resistivity. Fig. 3 shows the current and potentials at the feed point when the grid is hit alternatively in the middle and the corner point. All computed values are normalized to the current pulse peak value I_m.

If the dynamic performance of the grid is identical to the low-frequency performance, then the potential at the feed point v would be independent of the feed point position and purely resistive (i.e., equal to iR) (dotted line in Fig. 3). However, the dynamic behavior seen in the initial microseconds of the strike in the Fig. 3 example is dominantly inductive because the potential pulses related to the central and corner strike (broken lines in Fig. 3) lead the current pulse (full line in Fig. 3) and, during the initial surge period, are larger than the resistive part of the potential iR (dotted line in Fig. 3). The values of v larger than iR show the extent of the impairment of the performance in comparison to low-frequency performance. The peak values of the normalized potential pulses in Fig. 3, v/I_m, are equal to Z, which is 2.32 Ω for the strike in the middle and 4.49 Ω for the strike in the corner. The computed low-frequency grounding resistivity of this grid is $R = 0.22$ Ω, and, therefore, $A \approx 10$ for the strike in the middle and $A \approx 20$ in the corner. The values of A are the maximal rates of impairment of the grounding performance, in comparison to the low-frequency performance during the first moments of the strike.

Fig. 4 shows the dependence of the inductive behavior on the lightning current waveform front time. The subsequent stroke current waveform has a fast front that results in a large peak value of the potential pulse. The much slower front of the first stroke current waveform results in much a smaller value of the potential pulse peak.

Fig. 5 illustrates the dependence of the impulse impedance on the grid size. For small grids, the value of the impulse impedance Z is similar to the low-frequency grounding resistance R. As the size of the grid increases, the values of Z and R decrease, but when a certain size of the grid equal to the effective area is reached, the value of Z becomes nearly constant for any further increase in the size of the grid. The effective area is smaller for the subsequent return stroke current waveform than for the first stroke.

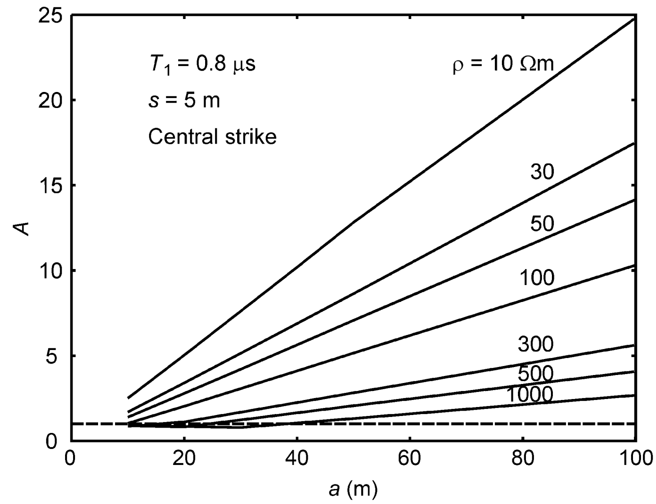

Fig. 6. Impulse coefficient of square grounding grids fed at the center with a subsequent return stroke current pulse for different values of soil resistivity. The separation of conductors is 5 m.

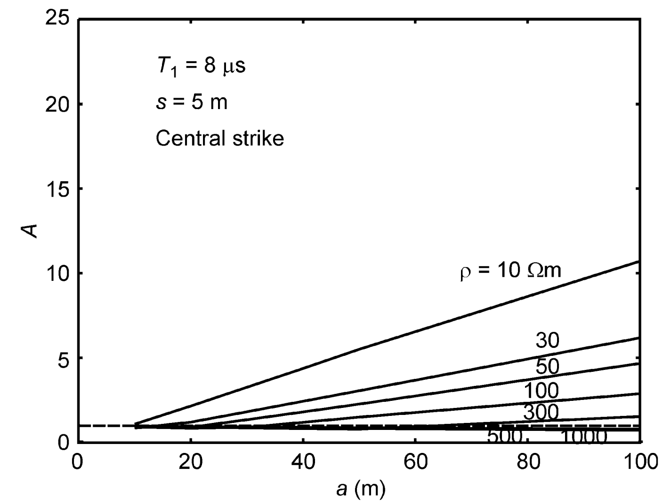

Fig. 7. Impulse coefficient of square grounding grids fed at the center with a first return stroke current pulse for different values of soil resistivity. The separation of conductors is 5 m.

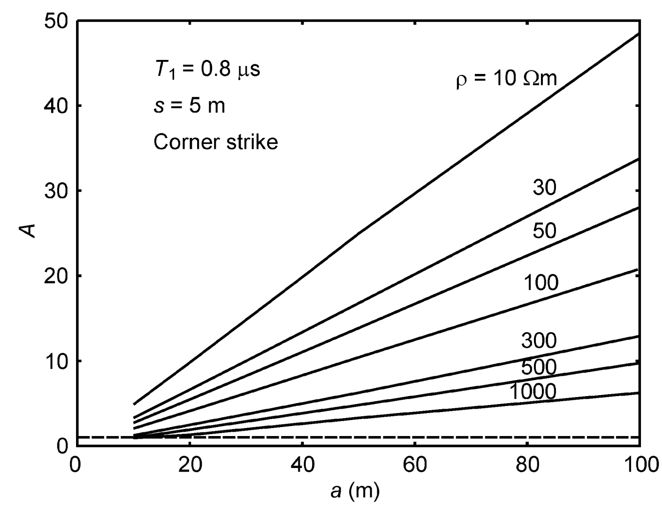

Fig. 8. Impulse coefficient of a square grounding grids fed at the corner with a subsequent return stroke current pulse for different values of soil resistivity. The separation of conductors is 5 m.

IV. Impulse Coefficient

For grid sizes smaller than the effective area, Z is equal to or less than R and, consequently, the impulse coefficient A (2) is nearly equal to or less than 1, as depicted in Fig. 5. For grid sizes larger than the effective area, Z is nearly a constant while R continues to decrease with the grid size. Consequently, A becomes larger than 1 and increases with the grid size.

A simple approximation of R is [30]

$$R = \frac{\rho\sqrt{\pi}}{4a}. \tag{3}$$

When Z becomes nearly constant for larger grid sizes (e.g., the broken and dotted lines in Fig. 5), A can be approximated as

$$A = \frac{Z}{R} \approx \frac{const.}{\rho\sqrt{\pi}} \times 4a \tag{4}$$

which suggests nearly linear dependence of A on a.

The simulation results in Fig. 6 confirm the behavior of A predicted by (4). A can be approximated by linear functions of a with a larger slope for better-conducting soils.[1] Notably, similar behavior has been also observed for simple grounding electrode arrangements in recent theoretical [6] and experimental [31] studies.

The results in Fig. 6 predict a large impairment in the grounding surge performance in comparison to the low-frequency performance for large grids, especially in more conductive soil. It is important to point out the relative meaning of this conclusion (i.e., the impairment of the surge performance of large grids in conductive soil is related to the good low-frequency performance).

The results in Fig. 7 illustrate the great influence that the lightning current front time has on values of A. It clearly illustrates that the large values of A in Fig. 6 are related to very fast front current pulses, such as subsequent return strokes. The results in Fig. 7 also show values of A that are less than 1 in very resistive soil, which may be attributed to the capacitive behavior that practically improves the grounding performance in the initial surge period [9]. Notably, this effect was confirmed in a recent experimental study [31], where an A in range of 0.3 to 0.9 was found for electrodes shorter than the effective length in the soil ρ range from 100 to 4000 Ωm.

It is well known that a lightning strike point positioned at the edge of the grid leads to increased values of A. The results in Fig. 8 for a corner-positioned strike point show a doubling of A in comparison to the corresponding central strike point in Fig. 6.

A comparison of the results between Figs. 6 and 9 illustrates that a reduction of the conductor separation from 10 to 5 m in the considered grids does not have a significant influence on A. The values of A are somewhat reduced for $s = 5$ m (Fig. 6) in comparison with $s = 10$ m (Fig. 9) for values of soil resistivity equal to and larger than 100 Ωm. On the other hand, for values of soil resistivity smaller than 100 Ωm, the values of A are somewhat larger for $s = 5$ m than for $s = 10$ m because Z is unchanged while R is slightly smaller for the denser grid. This effect is further discussed in the following section.

[1]Note that in all simulations in this paper, R is obtained by the electromagnetic model [17]. A simple approximation (3) is used only in (4).

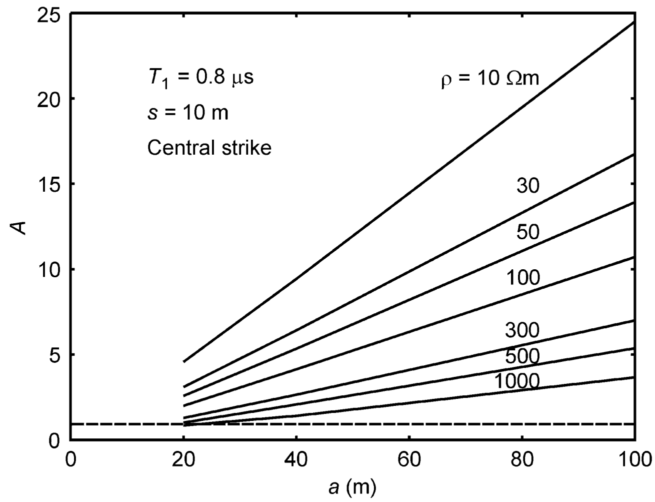

Fig. 9. Impulse coefficient of the square grounding grids fed at the center with a subsequent return stroke current pulse for different values of soil resistivity. The separation of conductors is 10 m.

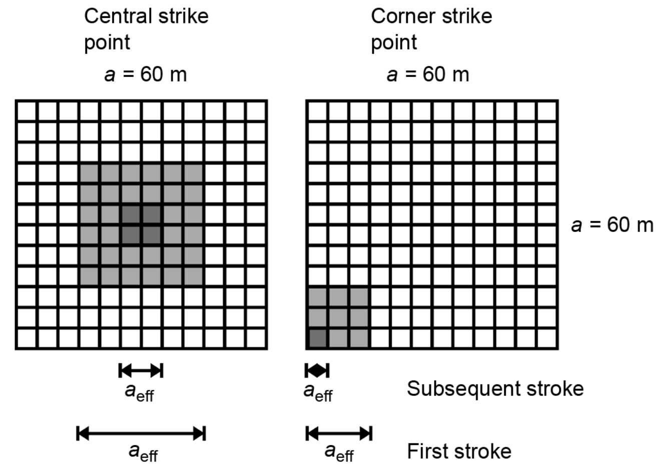

Fig. 10. Effective area of the grounding grids.

V. Effective Area

Gupta and Thapar defined the effective area as the "limiting area of the grounding grid around the feed point which is effective in controlling the impulse impedance" [9]. Importantly, the effective area is not directly related to the area of conductors that is effective in discharging the impulsive current; such an area changes rapidly. The area originates at the injection point at the beginning of the lightning strike and expands with the speed of propagation of the current pulse over the conductors. This speed is high—it is only slightly slower than the speed of light. This process of current propagation over the grounding grid lasts only for a few microseconds on average. After this short initial surge period, during the later stationary phase of the strike, the entire area of the grounding grid is effective in discharging current to the earth. The interested reader can find a computer-animated illustration of this in [4, Figs. 10 and 11].

Following Gupta and Thapar's definition [9], we determine the side length of the effective area of the grid $a_{\rm eff}$ as the value of a when $A = 1$.

One practical meaning of the effective area is that it is the area of the grid within which it is possible to reduce the impulse impedance Z by employing denser meshed conductors (see the examples in [28] and [32]). For that reason, we consider the grid's effective areas in forms as illustrated in Fig. 10.

The effect of reduction of Z by employing denser meshed conductors within the effective area explains the somewhat smaller values of A for $\rho \geq 100\ \Omega$m in grids with conductor separation $s = 5$ m in Fig. 6 in comparison to the grid with $s = 10$ m in Fig. 8. $a_{\rm eff}$ for $\rho \geq 100\ \Omega$m is larger than roughly 10 m, and a denser mesh with $s = 5$ m is within the effective area which, to some extent, reduces Z and, accordingly, A. Conversely, $a_{\rm eff}$ for $\rho \leq 30\ \Omega$m is smaller than about 5 m, and the modification of the grid is out of the effective area, and the effect of reduction of the value of A does not exist.

TABLE I
Input Parameters of the Proposed Formulae (5)–(7)

Parameter	Symbol	Unit	Validity range
Square grid side length	a	m	5 – 100
Soil resistivity	ρ	Ωm	10 – 1000
Current pulse zero-to-peak time	T_1	μs	0.2 – 10

VI. Empirical Formulas

Simple new empirical formulas for $a_{\rm eff}$ and A are deduced from the simulation results so that

$$a_{\rm eff} = K \cdot \exp\left[0.84 \cdot (\rho T_1)^{0.22}\right] \tag{5}$$

where

$K = 1$ center-fed grid;

$K = 0.5$ corner-fed grid.

Here, $a_{\rm eff}$ is in meters. Units of other parameters in (5) are given in Table I.

When the grid side a is smaller than the side of the effective area $a_{\rm eff}$, we approximate the value of the impulse coefficient by

$$A = 1 \quad (a \leq a_{\rm eff}). \tag{6}$$

For a being equal to and larger than $a_{\rm eff}$, the impulse coefficient is approximated by

$$A = \frac{a}{a_{\rm eff}}, \quad (a \geq a_{\rm eff}). \tag{7}$$

Input parameters for the proposed formulas (5)–(7) and their validity ranges are given in Table I.

The impulse impedance can be determined from (5)–(7) for a known low-frequency grounding resistance R where

$$Z = A \cdot R, \tag{8}$$

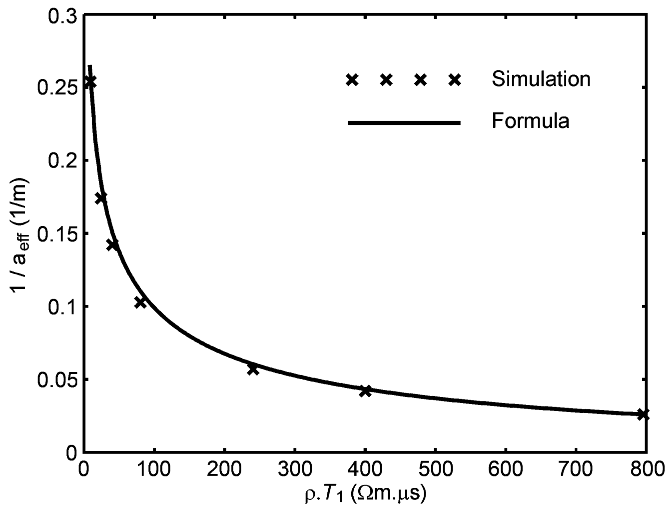

Fig. 11. Simulation data and formula (5).

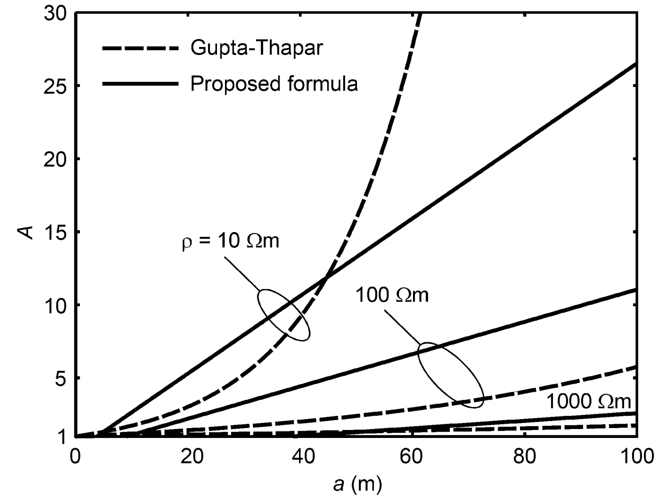

Fig. 12. Comparison between formulae for the impulse coefficient of square grids fed at the central point: (10) given by Gupta and Thapar in [6] and (5)–(7) proposed in this paper.

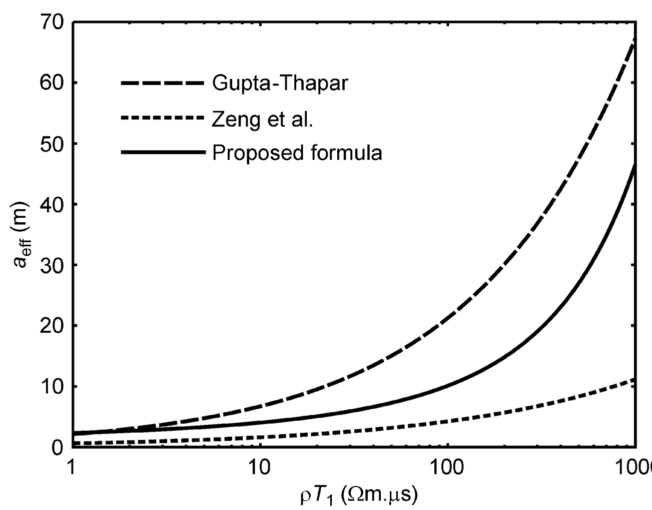

Fig. 13. Comparison between formulas for the effective area of square grids fed at the central point: (11) in [9], (12) in [10], and (5) proposed in this paper. A fixed value of $T_1 = 0.8\ \mu$s is used in (12).

and the maximal elevated surge potential at the feed point V_m for a known lightning current peak value I_m is

$$V_m = Z \cdot I_m. \tag{9}$$

The coefficients in (5) do not have any physical meaning; they are determined by curve fitting to the simulation data. Fig. 11 illustrates some of the simulation data for a central strike point (Fig. 6) used for the estimation of (5) by curve fitting.

A comparison of the values of A for different conductor spacing suggests small effects on A for the considered range of values (s = 5-10 m) (e.g., in Figs. 6 and 9). Similarly, simulation data suggest a negligible influence of the grid depth in the range from 0.5 to 1 m. It is also known that the conductors' radius does not have much of an effect on A [9]. All of these effects are neglected in (5)–(7).

VII. Relation to Previous Work

Formulas for the impulse coefficient and effective area have been given by Gupta and Thapar in [9], that is, for the impulse coefficient

$$A = \exp\left[0.333\left(\frac{a\sqrt{\pi}}{a_{eff}}\right)^{2.3}\right] \tag{10}$$

and for the effective area

$$a_{eff} = (1.45 - 0.05s) \cdot \sqrt{\pi\rho T_1}. \tag{11}$$

Notably, (10) proposes exponential dependence of A on a, which does not agree with the dominant linear dependence suggested by (4).

Another formula for the effective area has also been proposed in [10][2] as

$$a_{eff} = 0.34\sqrt{\pi} \cdot \rho^{0.42} T_1^{0.34}. \tag{12}$$

[2]Note that (10)–(12) have been adapted to the definition of the effective area used in this paper.

The comparison of the formula for the impulse coefficient (10) and the formula proposed in this paper (5)–(7) is illustrated in Fig. 12. The compared values of A are different for different values of soil resistivity, except for large soil conductivities, such as $\rho = 1000\ \Omega$m, when values of A are relatively small.

Fig. 13 compares the different formula results for effective area (11) suggested by Gupta and Thapar in [9], (12) by Zeng *et al.* in [10], and proposed in this paper (5). Different formulas estimate similar trends but give different results.

The differences in the results in Figs. 12 and 13 may be attributed not only to the different underlying simulation methods (i.e., circuit methods in [9] and [10] as well as the electromagnetic method in this paper), but also to the differences in definitions of the effective area (see discussion in [10, p. 674]).

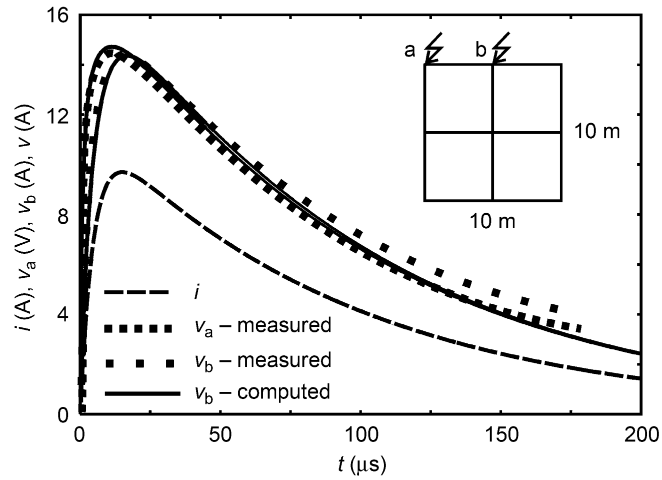

Fig. 14. Comparison of measured transient potentials of the square grounding grid [33].

VIII. Comparison With Experimental Data

The simulation method used in this paper has been previously compared with a number of published experimental data for reference. The reader is referred to previous publications (e.g., [4], [7], and [24]), where the comparisons are described and where good agreements between computed and experimental results have been reported. In this paper, we present one additional comparison between the computed and experimental results.

We compare our results with experimental data in [33]. Fig. 14 shows a comparison of the computed and measured transient potential at two alternative current feed points. The square grounding grid has 10-m sides and four meshes that are constructed of copper conductors with 4-mm radii and buried at a depth of 0.5 m. The soil resistivity of the equivalent uniform model is estimated to be 35 Ωm from the measured low-frequency grounding grid resistance of 1.72 Ω. The current impulse i is approximated by a double exponential pulse with $\mathrm{T_1/T_2} = 10\ \mu$s/85 μs, which is injected alternatively at two points, denoted by "a" and "b" in Fig. 14. The computed results for the potentials at the two feed points are consistent with the measurements.

The measured current and voltage peak are $I_m = 10.4$ A and $V_m = 1.72$ V, respectively. Consequently, measured values of impulse impedance and impulse coefficient are $Z = 1.65\ \Omega$ and $A = 0.96$. To check the new formula (5), we compute the effective area, which is $a_{\mathrm{eff}} = 21$ m. Therefore, for $a < a_{\mathrm{eff}}$, we calculate $A = 1$ (6), which is a conservative estimate of the measured A.

IX. Conclusion

Two phenomena are important in the dynamic behaviors of grounding systems: 1) soil ionization that may improve grounding performance and 2) inductive behavior that may impair surge performance. However, it has been suggested in recent publications that the effect of soil ionization is likely to be small and can therefore be ignored for grounding grids in high-voltage substations.

The inductive effects are enhanced for fast front current pulses, such as subsequent return strokes. The analysis of these fast front pulses might be out of the validity domain of circuit theory-based models. In this paper, we apply a more accurate model based on a rigorous electromagnetic theory approach, which is applicable for very fast front current pulses.

The analysis of the results of the computer simulation suggests a new relationship between the impulse coefficient of the square grounding grids and the side length of the grids, which can be approximated by a linear function.

New simple empirical formulas for the impulse coefficient, impulse impedance, and effective area of square grids are proposed on the basis of computer simulation results for a large number of test cases.

The new formulas are able to identify a combination of parameters for which large impairments of lightning surge performance in comparison to low-frequency performance are possible.

Successful validation of the simulation method used for derivation of the new formulas in comparison with a large amount of experimental data from different research groups suggests that the new formulae may be used for a first check in the lightning performance calculations of grounding grids.

Notably, the effects of nonlinear and frequency dependence of soil parameters and the capacitive behavior are neglected in the empirical formulae. Since all of these phenomena could improve the impulse performance in view of all other necessary assumptions, this approximation might be conservative.

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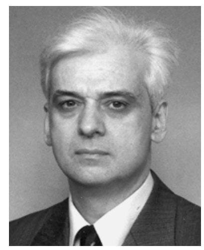

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