Frequency Dependent and Transient Characteristics of Substation Grounding Systems

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Abstract—**In spite of the existence of a number of analytical models aimed for transient analysis of large grounding systems, more detailed analysis of the influence of different parameters on the transient performance of large ground grids subjected to lightning current impulse is not available. This paper presents analysis of the influence of soil conductivity, location of feed point, grid size, depth, conductor separation, ground rods, and shape of the lightning current impulse, on the transient performance of ground grids with sizes ranging from 10 x 10 m^2 to 120 x 120 m^2 and with 4 to 124 meshes. Maximal transient ground potential rise and frequency dependent impedance are analyzed in time and frequency domain, respectively. Computations are made with computer model based on the electromagnetic field theory approach, taking accurately into account frequency dependent characteristics of large ground grids. Instead of usual simple approximations of the lightning current impulse, recorded channel base currents from triggered lightning are used for the time domain analysis.**

KEYWORDS – Substation, Grounding, Transient Performance, High-Frequency Performance, Impedance, Transient GPR, Lightning, Computer Simulation, Lightning Protection, EMC.

I. INTRODUCTION

Ground grids are considered as an effective solution for grounding systems of substations and plants [1]. An ideal grounding system should provide near zero impedance to remote neutral ground and even voltage distribution at its surface. However, in practice the impedance of the grounding systems to earth is always larger than zero and the distribution of voltages may be highly uneven during the transient period. The resulting voltages between different points at grounded structures may generate hazardous conditions for the human beings and the equipment, in case of power system abnormal operation or lightning [2].

Grounding systems behavior at industry frequencies (50 or 60 Hz) is well understood [3]. Analysis of grounding systems subjected to lightning current impulse is considerably more complicated, and most of the previous work on this subject is based on numerous simplifications. A great part of the previous work on this subject relates to simple grounding arrangements, such as linear horizontal electrodes and ground rods [4]–[7]. Complex ground arrangements, such as, ground grids, are analyzed recently in [8]–[14]. While, analysis in [8] and [9] is based on empirical approach, other approaches are analytical, based on: circuit theory ([10], [11]), and transmission line theory ([12]–[14]). However, all these analytical approaches ([4]–[7] and [10]–[14]) are based on quasi-static approximation. Consequently, their validity may be limited to some upper frequency which depends on the size of the grounding system and the electrical characteristics of the earth [15]. More recently, formulations derived from the full set of the Maxwell's equations has been used [16]-[22]. Voltages and fields at the soil surface are analyzed in [20] and [21], and effects of aboveground structures are analyzed in [22]. This rigorous approach highly surpasses the limitations of the previous more simplified approaches, but is more complicated for use. However, although methods for analysis of large grids are described in the above mentioned publications, more detailed analysis of the influence of parameters on the performance of large ground grids is not available.

The purpose of the study in this paper was twofold. The first was to investigate the influence of different parameters to enable better understanding of the transient performance of large ground grids. The second was to analyze response to realistic lightning current impulses, such as recorded triggered-lightning impulses [23].

The computations in this study are made using model [19], based on the electromagnetic field approach, that includes fewer simplifications than the most of the previous models. Reader is referred to [19] for full details on the model and its validation by comparison with field measurement and with other authors' models.

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II. FREQUENCY DEPENDENT IMPEDANCE AND TRANSIENT GROUND POTENTIAL RISE

Usually, a first step in analysis of the safety of electric power installations is to determine the highest possible elevation of the voltage between the grounding system and the remote neutral earth, that is, "the ground potential rise" (GPR). In low frequency case the GPR is a single number, since the grounding systems usually are assumed equipotential [3]. In case of lighting, the transient GPR is a complex three-dimensional time-domain function [19].

For comparison of the transient performance of different grounding systems and analysis of the influence of different parameters, two parameters may be used. The first one is the maximal transient GPR, that is, GPR at the feed point. However, one difficulty with this parameter is that it is dependent on the specific shape of the current impulse that energizes the grounding system. Besides, since GPR is by definition scalar potential, care should be taken to extract the influence of the path-dependent term of the voltage to remote neutral ground, as discussed in [19]. Second parameter is the grounding impedance, defined as a frequency dependent transfer function, according to suggestions in [24] and [25]. Its main advantage is that it is dependent only on the geometry of the system and the electromagnetic characteristics of the soil and is independent of the excitation. Furthermore, it enables evaluation of transient GPR as a response to an arbitrary excitation.

Frequency dependent grounding system impedance may be defined as:

$$Z(j\omega) = V(j\omega)/1\text{A} \tag{1}$$

where $V(j\omega)$ is maximal GPR at feed point, obtained as response to time-harmonic steady-state 1 A current in a frequency range of interest for the transient study. If $Z(j\omega)$ is known, then transient GPR at feed point $v(t)$, as response to arbitrary excitation $i(t)$, may be straightforwardly obtained. If Fourier transform technique is used then [17]:

$$v(t) = \mathcal{F}^{-1}\left\{Z(j\omega)\cdot\mathcal{F}\left[i(t)\right]\right\} \tag{2}$$

where $\mathcal{F}$ and $\mathcal{F}^{1}$ are Fourier and inverse Fourier transform, respectively.

Grounding system impedance is obtained in [4] and [13] from the step or impulse response of the grounding system, by transforming the time-domain response to frequency-domain. Here the grounding system impedance (1) is directly obtained by analysis in frequency-domain. The GPR at feed point $V(j\omega)$ (1) is computed using computer model described in [19].

Neglecting the non-linearity of the soil due to ionization is an inherent part of the definition of the frequency dependent grounding system impedance. For large enough currents the ground conductor surface electric fields may become greater than the ionization threshold of approximately 300 kV/m [26], and ionization of the soil may occur. This limits the intensity of $i(t)$ (2) that can be analyzed using $Z(j\omega)$ [27].

III. CURRENT IMPULSES ADOPTED FOR COMPUTATION

Lightning current impulses may be characterized by their polarity, amplitude, rise-time and duration. Negative flashes usually consist of multiple strokes with typical inter-stroke intervals ranging from tens to hundred milliseconds. The first stroke has the highest amplitude, while the subsequent strokes have faster rise times. Positive flashes usually consist of a single stroke, with much higher amplitudes and slower rise times. It has been accepted that the majority of lightning flashes have negative polarity, and also majority of engineering applications are concerned with the lightning return stroke events [28].

Triggered-lightning is similar to return strokes in natural lightning, since both follow previously formed channel [23]. Five diverse waveshapes of channel base currents from recorded triggered-lightning [23] are chosen for computations, Fig. 1. All are return stroke pulses with fast front and slower tail. Curve B represents a typical pulse with 10–90% rise time 0.36 μs and time to half amplitude about 50 μs. Impulses A, B and C have different times-to-half-amplitude, while D and E are impulses with nontypical tail. Impulse C has shortest and D has longest rise time. All curves in Fig. 1 are normalized to the amplitude I_m.

Since the most probable lightning evens are related to return strokes, it may be of interest to consider use of recorded current waves, such as curve B in Fig. 1 or similar, in future analysis of responses to return stroke impulses.

IV. DESCRIPTION OF THE CASES ADOPTED FOR COMPUTATIONS

Several ground grids are adopted for computations with dimensions varying from 10 x 10 m^2 to 120 x 120 m^2 and with number of meshes from 4 to 124. All are constructed of copper conductors with diameter 1.4 cm and buried at 0.5 m depth. Two types of homogeneous soil are considered: with resistivity 1000 Ωm and relative permittivity 9 and with resistivity 100 Ωm and relative permittivity 36. The first soil model was referred as "dry soil" and the second as "wet soil" in [12]. Later the same models were also chosen in [20], [21] and [22]. Concerning the location of the feed point, two scenarios are considered: injection in the corner point, and, alternatively, in the center point of the grid. To investigate the influence of the depth of the grid, computations are also made for the depths 0.3 m and 1 m.

The influence of the aboveground structures is neglected, in contrast to [22], since the parametric analysis in this paper is meant for comparative purposes.

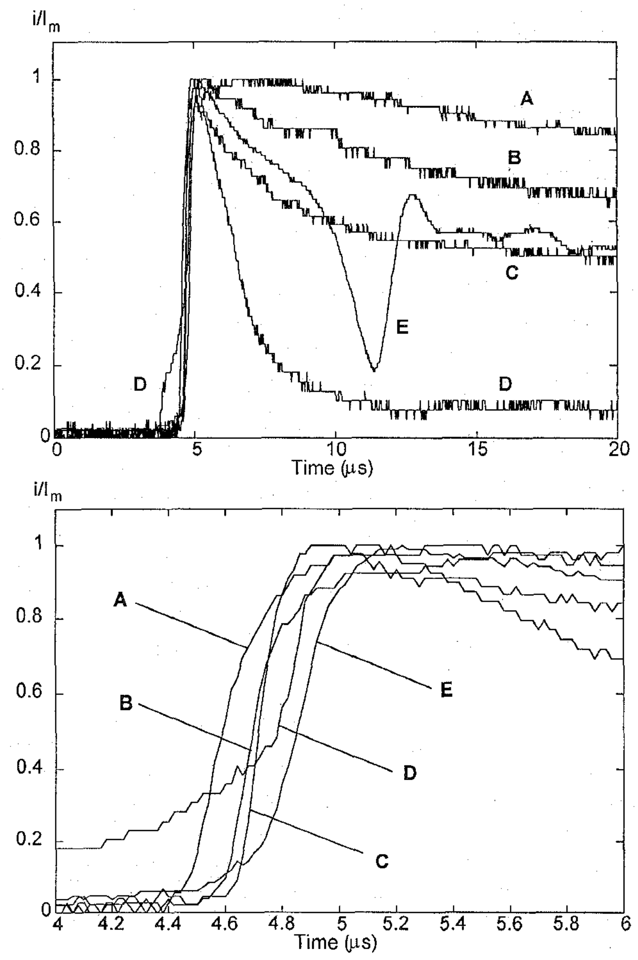


Fig. 1. Five Lightning Current Impulses Adopted for Analysis.

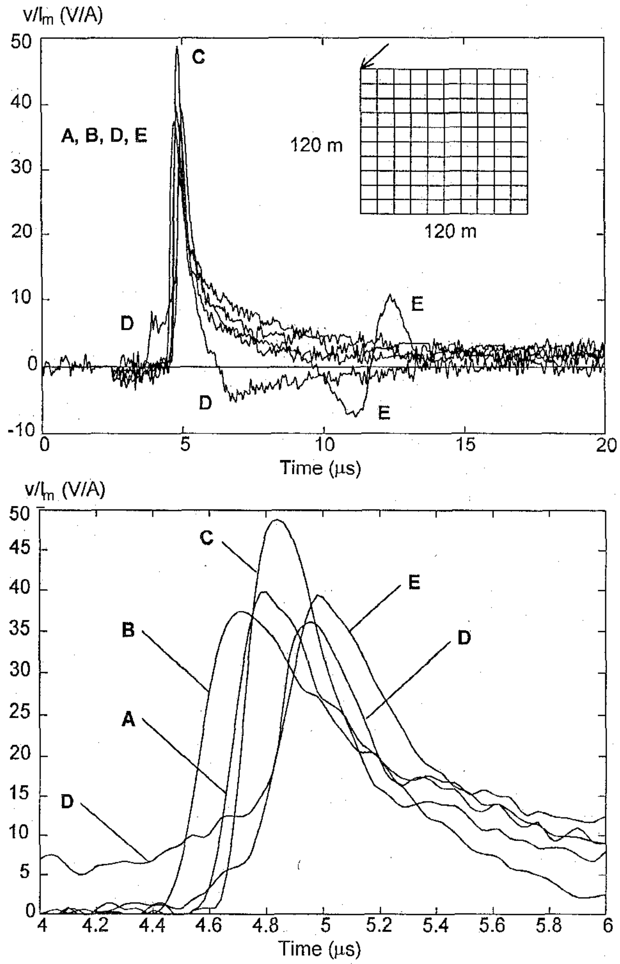


Fig. 2. Transient GPR as Response to Current Impulses in Fig 1.

V. INFLUENCE OF THE IMPULSE SHAPE

Fig 2. shows maximal transient GPR in 120 x 120 m^2 ground grid with 10 by 10 12 m square meshes as response to lightning current impulse B (Fig. 1). Current injection is in corner and grid is in soil with ρ =1000 Ωm and $\varepsilon_r = 9$.

Transient GPRs are impulses with large amplitudes (more than ten times larger than for power frequency), but with short duration (a few microseconds). Transient GPRs lead current impulses and their maximums occur during the rise of the current impulses. Maximums of the transient GPRs are dependent on the front time and the steepness of the current impulses, and are independent of the tail. Current variations at the tail are always much slower, compared with the rise, and induced voltage variations are with much smaller peaks (impulses D and E). Current impulse C, with shortest rise time, induces voltage with highest maximum. However, current impulse D, with longest rise time, but with steep 50-90% rise, induces voltage impulse with maximum similar to current impulse A, B and E, that have shorter rise times.

VI. INFLUENCE OF SOIL RESISTIVITY AND LOCATION OF FEED POINT

Influence of the soil resistivity and the location of the feed point on the frequency dependent impedance is illustrated in Fig. 3. It can be seen that two frequency ranges may be distinguished: "low frequency" range, where the impedance is nearly constant, and the "high frequency" range, where impedance is changing with frequency. In case of feed point at the corner of the grid, the "low frequency" range is up to 1 kHz for soil with ρ = 100 Ωm and to 10 kHz for soil with ρ = 1000 Ωm. Central feed point broaden the low frequency range for a factor of 10, i.e. to nearly 10 kHz for soil with ρ = 100 Ωm and to 100 kHz for soil with ρ = 1000 Ωm.

In the "high frequency" range the impedance is rising with frequency in the whole observed range. Impedance for corner feed point is two times higher than in case of central feed point. Speaking in circuit terms, impedance is dominantly "inductive" in the whole "high frequency" range, although the "capacitive" effects are becoming significant for the higher frequencies. While the ratio of the magnitudes of the impedance for soils with resistivities 100 Ωm and 1000 Ωm for low frequency part is 1:10, in high frequency range this ratio is becoming smaller.

The shape of frequency characteristics in Fig. 3 implies that the amplitudes in the spectrum of the response will be emphasized in the "high frequency" range. However, the actual shape of the time domain response depends on the frequency content of the excitation impulse.

The influence of soil conductivity and location of the feed point on the maximal transient GPR, as response to lightning current impulse B (Fig. 1), is shown in Fig. 4. The transient GPR is normalized to I_m, that is, the maximum of the lightning current impulse. The key parameters are given in Table I. The first column is normalized maximum of the transient GPR V_m/I_m, so called impulse impedance. The impulse coefficient α is defined as:

$$\alpha = \frac{V_m}{I_m \cdot R_{DC}} \tag{3}$$

where R_{DC} is low frequency resistance to ground. The approximate duration of the transient period is from the beginning of the transient GPR impulse until the time after which it is not substantially changed.

TABLE I. IMPULSE IMPEDANCE, IMPULSE COEFFICIENT AND APPROXIMATE DURATION OF TRANSIENT PERIOD OF 60 X 60 M^2 GRID

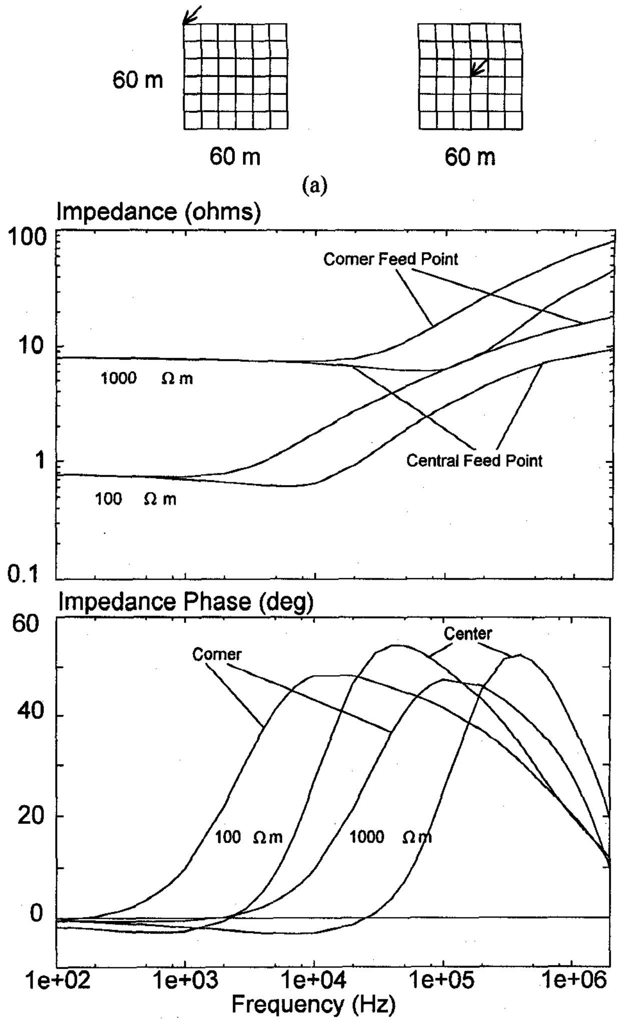
Soil Resist. (Ωm)	Feed Point	Impulse Imped. (Ω)	Impulse Coeff.	Transient Period (μs)
100	Center	5.44	6.9	3.1
100	Corner	9.54	12.1	6.6
1000	Center	18.2	2.3	1.1
1000	Corner	38	4.8	2.6

It can be seen that V_m is proportional to soil resistivity at longer duration (low frequency), while the sensitivity is reduced to about 40% for the frontal amplitude (high frequency). The maximal variation of the V_m with different locations of the feed point is approximately 1:2. Also as V_m is becoming larger in poorly conductive soil, the transient period is becoming shorter, due to larger velocity of propagation of electromagnetic pulses.

VII. INFLUENCE OF GRID SIZE

Influence of ground grid size on frequency dependent impedance is illustrated in Fig. 5. Five ground grids are chosen for computations, with dimensions ranging from 10 m by 10 m to 120 m by 120 m, Fig. 5 (a). All grids are in soil with ρ = 1000 Ωm and ε_r = 9. Feed point is at the corner.

Ground grid size has large influence on the low frequency value of impedance to ground, but in the high frequency range behavior of different ground grids after some frequency becomes very similar. Clearly, effective area of the ground grids is becoming smaller for higher



(a)

(b)

Fig. 3. Influence of Soil Conductivity and Location of Feed Point on Frequency Dependent Impedance. (a) Analyzed Ground Grids and Location of Feed Point. (b) Frequency Dependent Impedance.

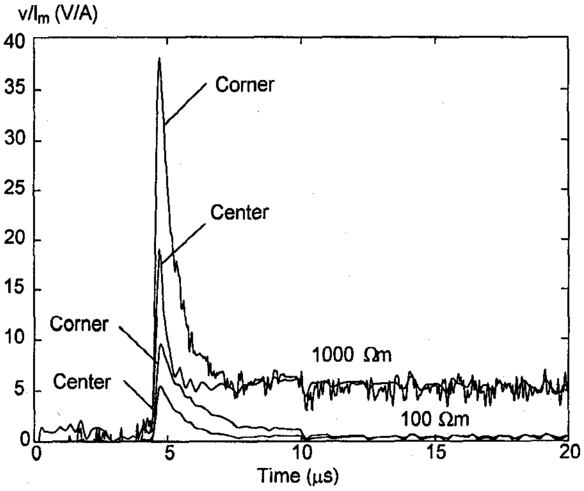


Fig. 4. Influence of Soil Conductivity and Location of Feed Point on Maximal Transient GPR as Response to Current Impulse B (Fig. 1).

frequencies. This point is also emphasized in the time domain analysis.

Fig. 6 illustrates the influence of the ground grid size on the transient GPR, as response to lightning current impulse B (Fig. 1). All impulses have fast rise to their maximums, and shortly after that (approximately after 1 to 5 μs) they tend to be near the value typical for dc excitation. The maximums of transient GPRs are equal for all grids with sizes from 20 x 20 m^2 to 120 x 120 m^2, which implies that the effective area of all analyzed grids is less than 20 x 20 m^2.

VIII. INFLUENCE OF CONDUCTOR SEPARATION

Influence of ground grid conductor separation on frequency dependent impedance is illustrated in Fig. 7. Five ground grids, with same dimensions (60 x 60 m^2) and number of meshes ranging from 4 to 124, are chosen for computations, Fig. 7 (a). All grids are in soil with ρ = 1000 Ωm and e_r = 9. Feed point is at the corner.

As it is well known, ground grid conductors separation has small influence on the GPR in the low frequency range, where dominant influence has the area of the grid. The similar conclusion is valid for the high frequency behavior of ground grids when the conductor separation is reduced from 30 m to 6 m. Greater influence in the high frequency range has further reduction of the conductor separation to 3 m near the feed point, that is, in the effective area.

Fig. 7 illustrates the influence of the ground grids conductors separation on the transient GPR, as response to lightning current impulse B (Fig. 1). Clearly, significant reduction of V_m is possible with smaller conductors separation only when meshes are significantly smaller than the effective area of the grid.

IX. CONCLUSIONS

1. Paper presents analysis of the influence of different parameters on the transient performance of substation ground grids subjected to lightning current impulse. Analysis is done by computer model [19], based on electromagnetic field theory approach, that accurately takes into account frequency dependent characteristics of the system.

2. The transient performance of different grounding systems is analyzed by comparison of the frequency dependent impedance and the maximal transient GPR. The frequency dependent impedance reveals characteristics dependent only on the geometry of the system and the electromagnetic properties of the soil and is independent of the excitation. The maximal transient GPR gives perception on possible maximal voltages between points at the ground grid conductors during the transient period, which is of special interest in EMC studies.

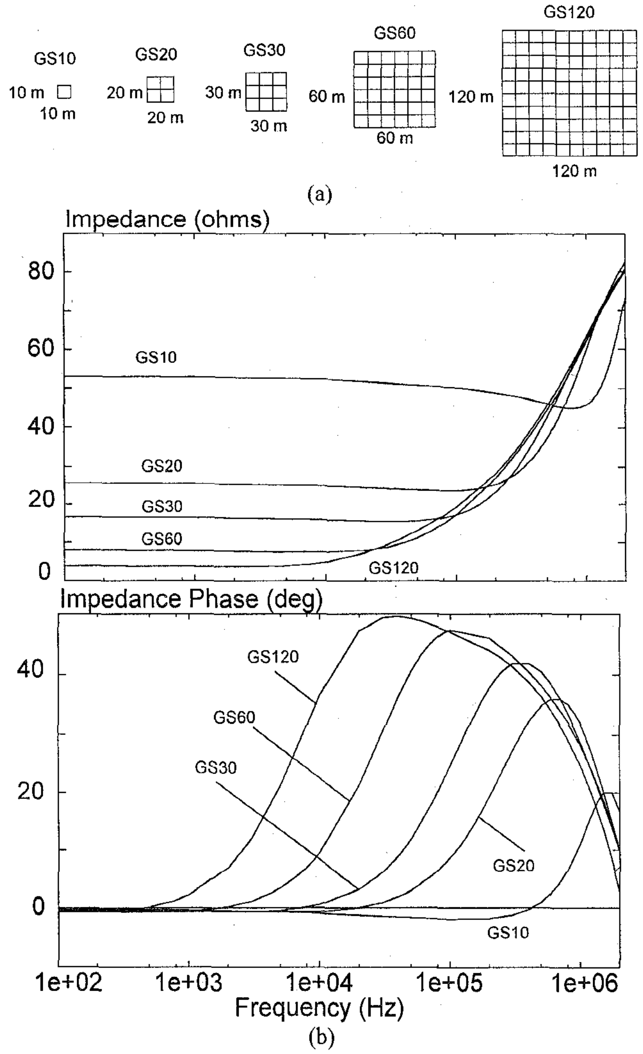


Fig. 5. Influence of Ground Grid Size on Frequency Dependent Impedance. (a) Analyzed Ground Grids and Location of Feed Point. (b) Frequency Dependent Impedance.

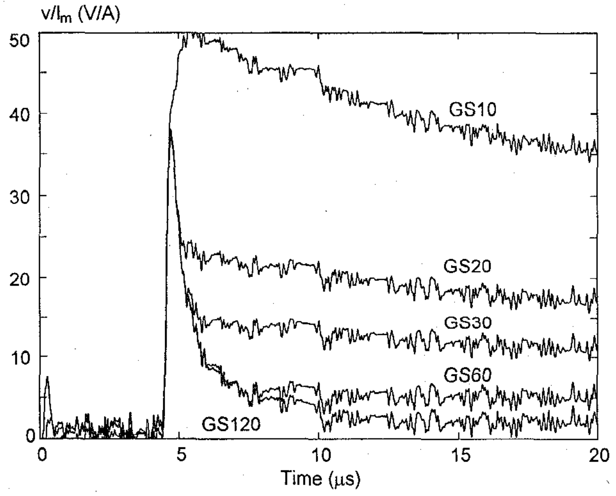
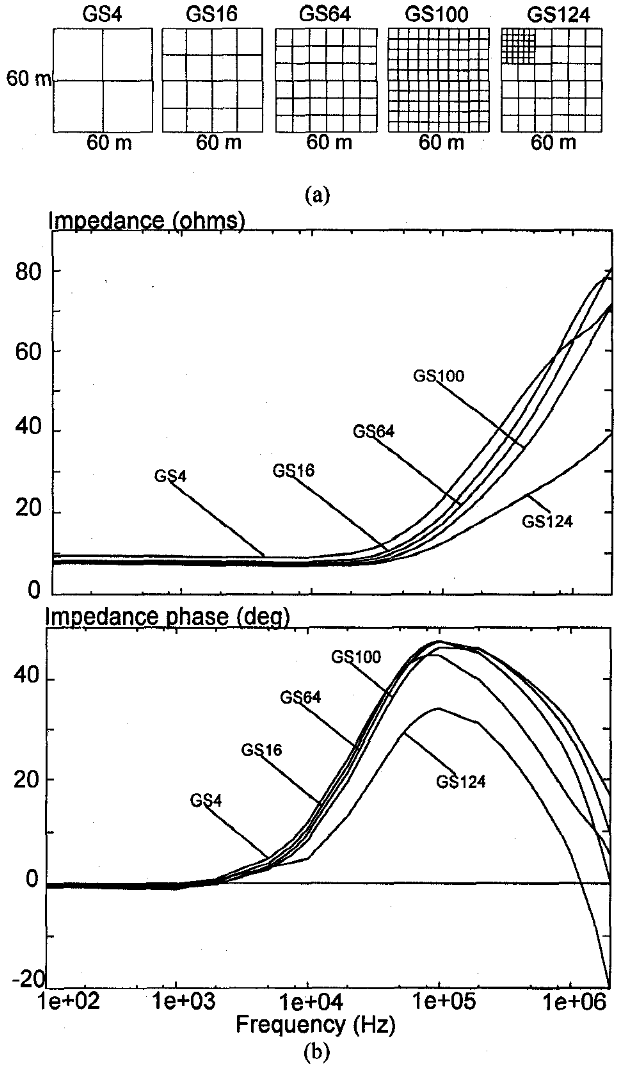


Fig. 6. Influence of Ground Grid Size on Maximal Transient GPR as Response to Lightning Current Impulse B (Fig. 1)



(b)

Fig. 7. Influence of Conductor Separation on Frequency Dependent Impedance. (a) Analyzed Ground Grids. (b) Frequency Dependent Impedance.

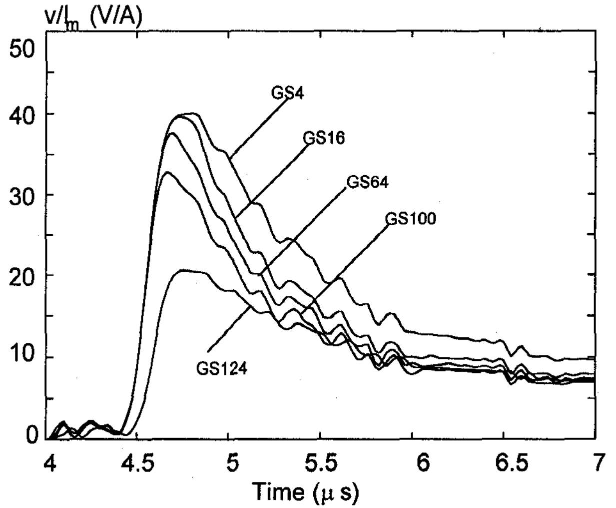


Fig. 8. Influence of Ground Grid Conductor Separation on Maximal Transient GPR as Response to Lightning Current Impulse B (Fig. 1)

3. Since majority of engineering applications are concerned with the lightning return stroke events, recorded triggered lightning currents, that are similar to return strokes in natural lightning, may be used in analysis of the response to return strokes.

4. Transient GPR is phenomenon associated with the rise of the lightning current impulse and does not depend on the tail. Fast variations of the current during the rise time may result in large impulse coefficients, but the transient periods are typically with short duration (in analyzed cases from few to ten microseconds).

5. Parameters that have the greatest influence on the transient performance of substation ground grids subjected to lightning current impulses are:

- soil resistivity (in dry and poorly conductive soil maximal transient GPRs are much higher than in wet and more conductive soil, but are with shorter transient period),
- shape of the current impulse front, more specifically, the average steepness of the impulse (not only the short rise time, but the high steepness of the current during part of the rise, induce higher voltages), and
- location of the feed point (maximums of the transient GPRs are approximately two times higher for feed point at the corner than at the center and the transient period is about two times longer).

6. The effective area of the ground grids in the analyzed cases was very small (less than 20 x 20 m^2 for feed point at the corner). The size of the ground grid, larger than the effective area, has no effect on the maximal GPR. However, impulse coefficient and duration of the transient period are larger for larger grids.

7. Smaller separation between conductors reduces significantly the maximal GPR only in case when meshes are significantly smaller than the effective area.

8. Depth of the ground grid has very small influence (smaller depth slightly reduces voltages) and ground rods at the ground grid perimeter have negligible influence.

9. The necessary frequency range is determined in [7] to few hundred kHz, based on spectral analysis of typical recorded oscillograms of negative polarity lightning current. However, computations in this paper could not be accurately done with frequency range smaller than 2 MHz.

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