TRANSIENT VOLTAGES COUPLING TO SHIELDED CABLES CONNECTED TO LARGE SUBSTATION EARTHING SYSTEMS DUE TO LIGHTNING

by

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Summary:

Paper presents a computer analysis of transient voltages coupled to buried shielded control cables in high-voltage substations subjected to lightning. It is based on recent advances in antenna theory approach applied to large substation earthing systems. Voltages and currents in shields are computed by the rigorous antenna theory approach and then voltages coupled to the control circuits are obtained by usual circuit theory approach. Influence of parameters, such as: lightning waveshape, soil conductivity, location of feed point, cable routing, earthing system size, and conductor separation, is investigated. Parameters with dominant influence are identified and possibilities for reduction of induced voltages are discussed. Relation between ground potential difference and field coupling components of the induced voltages is also investigated.

Keywords: Substation – Earthing – Control Cable – Shielding – Grounding – Lightning – Interference – Transient – Simulation

1. INTRODUCTION

The problem of protection of the electronic systems in HV substations against electromagnetic interference, in cases of power system abnormal operation or lightning, has been dealt with by many researchers, for example, [1]–[6]. This paper concentrates on transient voltages coupled to shielded cables in case of lightning. This problem can be divided in two parts:

- evaluation of the transient voltages and currents in the earthing system conductors, and
- evaluation of the transient voltages coupled to shielded cables.

The problem of coupling to shielded cables is well understood [7]. If the current or voltage in the shield is known, than induced voltages in the cable may be determined using the concept of transfer impedance or reduction factors, respectively [4], [8].

However, knowledge of the distribution of transient currents and voltages in large earthing systems subjected to lightning stroke is considerably less complete. Complex earthing arrangements are analyzed recently in [9]–[13]. While, work in [9] is based on empirical approach, other approaches are analytical, based on: circuit theory [10], transmission line theory [11], and antenna theory [12], [13]. The circuit and transmission line models are based on quasi-static approximation and their validity is limited to lower frequencies [14]. The antenna models are based on an exact formulation derived from the complete set of Maxwell's equations and enable more accurate analysis. Their main advantage is in analysis of electromagnetic interactions in structures of complex geometry.

The first purpose of the study in this paper is evaluation of currents and voltages along the shield by application of the rigorous antenna theory approach [13]. Voltages coupled to the control cables may be subsequently computed by usual simplified circuit modeling [8]. Another purpose was to investigate the influence of different parameters to enable better understanding of the EMC problems in large substations.

2. ANALYTICAL MODEL AND ITS VALIDATION

The physical situation is illustrated in Fig. 1. The earthing system is considered to be an arbitrary network of connected or disconnected buried conductors. Arbitrary routed shields are considered grounded at both ends. The analytical model is based on the antenna theory approach and is described in the recent publication [13]. The model

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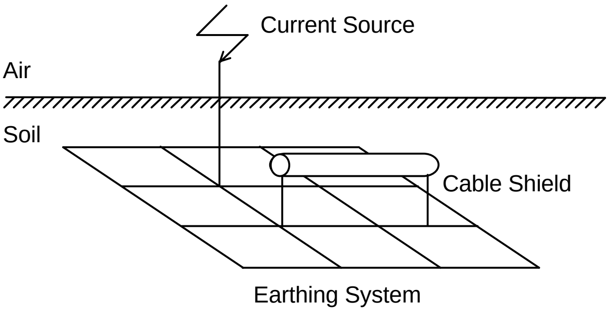


Fig. 1. Physical situation: lightning strikes above-ground structure connected to the earthing system and double-end grounded cable shield.

is validated by comparison with field measurements by EDF (Fig. 2) and with other authors' models [13].

2.1 Current distribution in the network of buried conductors

The transient problem is solved first in the frequency domain. To evaluate voltages, it is necessary to determine the current distribution in the earthing conductors. The first step in the analysis is to divide the whole structure into smaller segments, according to the well known method of moments [17]. Segments may be insulated or bare cylindrical conductors, metallic tubes or tubular shields with arbitrary orientation. The most important part is modeling of the mutual electromagnetic interactions between the segments. This leads to a matrix equation [13]:

$$[Z]\cdot[I]=[-Z_0 I_s] \qquad (1)$$

where the elements of the column matrix $[I]$ are unknown currents in segments. Elements of $[Z]$ express the mutual electromagnetic interactions between segments. Elements of $[-Z_0I_s]$ define the energization of the structure by the injection of currents I_s at arbitrary points. Reader is referred to [13] for full details on the model and its validation.

The neglect of the non-linearity of the soil due to ionization is an inherent part of the frequency domain approach. For large enough currents, the earthing conductor surface electric fields may become greater than the ionization threshold of approximately 300 kV/m [18], and ionization of the soil may occur. This phenomenon is neglected in all existing methods for transient analysis of large earthing systems, but further research is required to analyze its effects on induced voltages [19].

2.2 Modeling of interconnected earthing conductors and tubular shields

Antenna theory approach may be directly applied to single non-ferromagnetic tubular shields with or without dielectric coating. Details on the modeling of tubular shields may be found in [15]. The model was validated by comparison with other authors' models in [16].

One limitation is that the cables have to be "thin", i.e. their outer diameters have to be about ten times smaller than the length of smallest segment. Also lengths of the segments must be about ten times smaller than the smallest medium wave length.

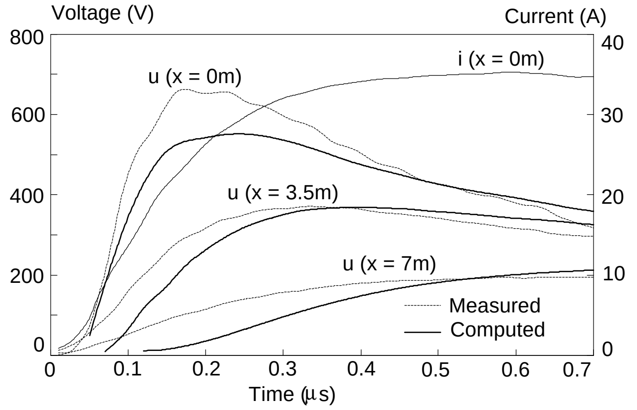


Fig. 2. Comparison with measurements by EDF. Measured and computed transient GPR at three points along horizontal copper wire (15 m length, 1.2 cm radius, 0.6 m depth, 70 Ω.m soil's resistivity, 15 soil's relative permittivity).

2.3 Computation of the transient response

If transient voltage $v(t)$ is required, then corresponding transfer function $Z(j\omega)$ in frequency domain is first obtained:

$$Z(j\omega) = V(j\omega)/1\text{A} \qquad (2)$$

Here $V(j\omega)$ is voltage as a response to a time-harmonic steady-state 1 A current excitation in a frequency range of interest for the transient study. If $Z(j\omega)$ is known, than $v(t)$, as response to arbitrary excitation $i(t)$, may be straightforwardly obtained:

$$v(t)=F^{-1}\{Z(j\omega)\cdot F[i(t)]\} \qquad (3)$$

where F and F^{-1} are Fourier and inverse Fourier transforms, respectively.

3. DESCRIPTION OF THE CASES ADOPTED FOR ANALYSIS

Fig. 3 illustrates the earthing grid adopted for analysis. Two types of homogeneous soil are considered: with resistivity ρ = 1000 Ω.m and relative permittivity ε_r = 9, corresponding to "dry" soil, and with ρ = 100 Ω.m and ε_r = 36, corresponding to "wet" soil [11]. 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. Two alternative cable routings are considered between points 1 and 3. Cables are buried at 0.3 m depth and the shield is bonded to the ground grid at both ends. The lightning current waveshapes adopted for computations are illustrated in Fig. 4.

4. CURRENT DISTRIBUTION ALONG TUBULAR SHIELD

As an example, longitudinal currents at three points along the shield (1, 2 and 3, Fig. 3), as response to T_1/T_2 =.25/100µs lightning current impulse with maximum I_m,

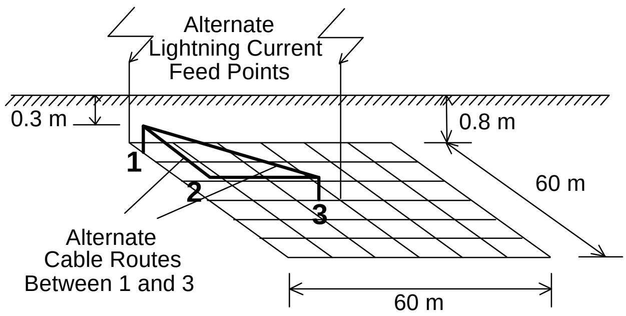


Fig. 3. 60 x 60 m^2 earthing grid with 6 x 6 10 square meshes at 0.8 m depth, constructed or copper conductor with 1.4 cm diameter. Cable shield is double-end grounded at points 1 and 3, and is buried at 0.3 m depth. Two alternative cable routes (1-2-3 and 1-3) and two alternative lightning current feed points (at the corner and at the center of the grid) are shown.

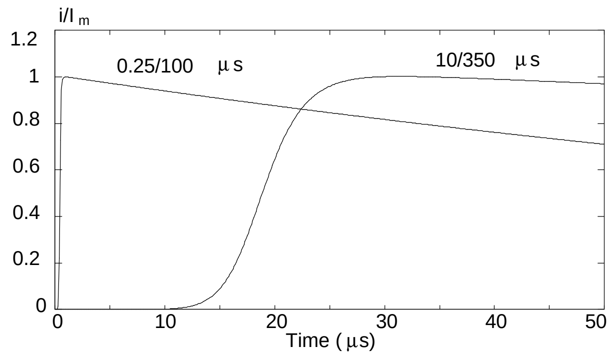


Fig. 4. Two lightning current waveshapes defined in IEC Standard [20] adopted for analysis. (First stroke: T_1/T_2 = 10/350 µs; subsequent stroke: T_1/T_2 = 0.25/100 µs).

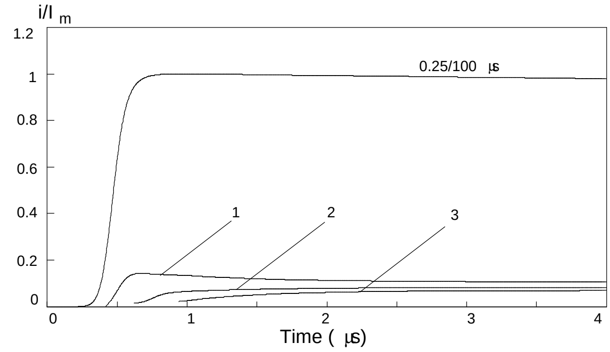


Fig. 5. Lightning current injected at the corner of the 60 x 60 m^2 grid in soil with ρ = 1000 Ω.m and ε_r = 9, and longitudinal currents at three points (1, 2 and 3) along bare metallic tubular shield (Fig. 3). Currents are normalized for I_m (the maximum of the lightning current impulse).

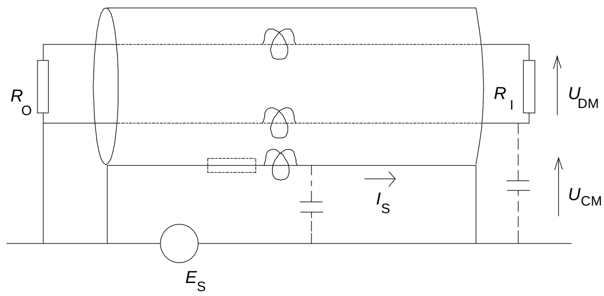


Fig. 6. One example of circuit representation of single double-end grounded shield [8]. R_O and R_I – output and input resistances, I_S – longitudinal current in the shield , E_S – voltage between shield's end points, U_{CM} – common mode voltage, U_{DM} – differential mode voltage.

are shown in Fig. 5. The shield is a bare copper tube with diameter 3 cm and 1 mm wall. Approximately 25% of the partial lightning current in the earthing conductor at point 1 is captured by the shield. The behavior of the current is different along the shield, and if circuit modeling is applied, the shield should be segmented to smaller segments.

5. COMMON AND DIFFERENTIAL MODE VOLTAGES

Fig. 6 illustrates one example of circuit modeling of double-end grounded shield [8]. When the current in the shield I_S is known then the common mode voltage coupled to the shielded cables U_{CM} may be computed using known transfer impedance Z_T [4], [7], [8]:

$$U_{CM} = Z_T \cdot I_S \tag{4}$$

Direct application of the antenna theory approach is limited to simple tubular non-ferromagnetic shields. Since in practice cables may be screened by multiple shields, conduits, trays or wires with different forms, it is advantageous to combine the antenna theory approach with the usual circuit modeling. For example, if the voltage along shield is known than common and differential mode voltages may be determined by known reduction factors [8].

Therefore the influence of different parameters on the voltages induced in the shielded cables may be studied by studying the voltage along the shield.

6. VOLTAGE BETWEEN SHIELD'S END POINTS

Total voltage V_T between the shield's end points 1 and 3 along the shield (Fig. 3) may be expressed as sum of two terms [21]:

$$V_T = (\Phi_1 - \Phi_3) + \frac{\partial}{\partial t}\int_\ell \vec{A} \cdot d\vec{\ell} = \Delta\Phi + V_\ell \tag{5}$$

where $\Delta\Phi = \Phi_1 - \Phi_3$ is difference between ground potential rise (GPR) at points 1 and 3, and V_ℓ is field coupling term due to time-varying currents in earthing system conductors. The first term $\Delta\Phi$ is uniquely defined, but the second term V_ℓ is path dependent. In this analysis, field coupling due to above ground sources is neglected.

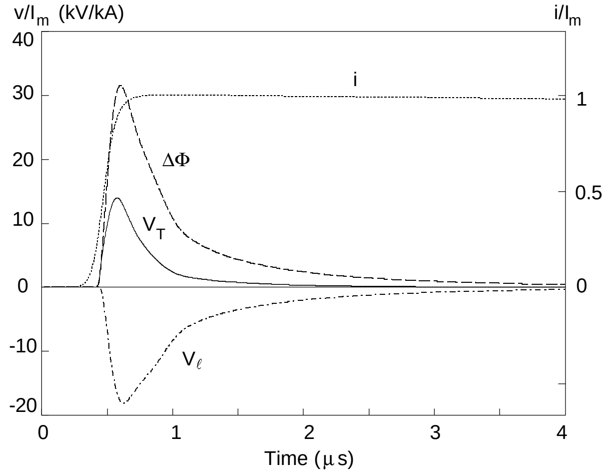


Fig. 7. Voltage along the shield (cable route: 1-2-3). V_T – total voltage along shield; ΔΦ – scalar potential difference; V_ℓ – field coupled component; i – lightning current injected at the corner of the grid.

It can be seen from Fig. 7 that ΔΦ and V_ℓ are opposite, and the total voltage V_T is smaller than these two terms. ΔΦ has dominant influence on the total voltage V_T, but V_T is considerably smaller than ΔΦ due to the effect of V_ℓ.

Fig. 8 illustrates the influence of the cable routing on the total voltage. Since in route 1-3, the cable is not laid near earthing conductors, such as in case of 1-2-3 routing, V_ℓ is smaller and total voltage is nearer to the ΔΦ.

In case when the lightning current is fed at the center of the grid all voltages are considerably smaller, as in Fig. 9.

Fig. 10 illustrates voltages under same conditions as in Fig. 7, but for more conductive soil with ρ = 100 Ω.m and ε_r = 36. This example illustrates that better conductivity of the soil has very large influence on the reducing of the voltages in the cable shield.

Fig. 11 illustrates the influence of the lightning current impulse shape. The conditions are same as in Fig. 7, but the lightning current impulse has much smaller steepness (T_1/T_2 = 10/350 μs, Fig. 3). As it is well known, large induced voltages are phenomena related to fast varying currents, and slower varying currents induce smaller voltages.

7. TRANSIENT GROUND POTENTIAL RISE

The GPR difference between the shield's end points has dominant influence on the total voltage along the shield.

Fig. 12 shows the influence of the earthing grid size on the maximal transient GPR at the feed point. The grid size has large influence on GPR after the transient period, that lasts for about one to few μs, but has small influence during the transient period. Results indicate that, for the analyzed cases, the effective area of the grid at the time when the maximum GPR occurs, is very small and may be approximated as not much greater than about 10 x 10 m^2.

Fig. 13 shows that smaller conductor separation can be used to reduce the transient GPR only if meshes are

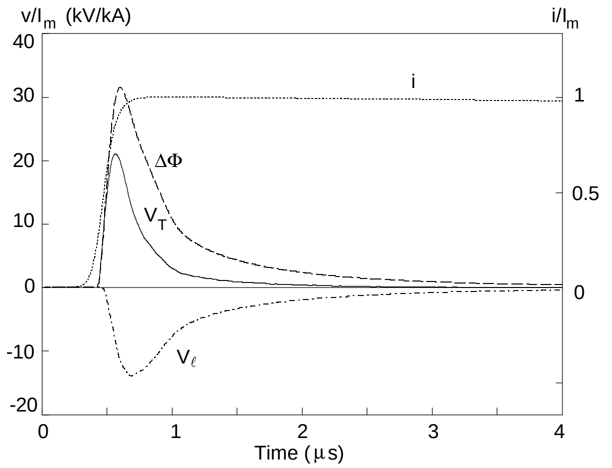


Fig. 8. Influence of the cable routing on voltage along the shield (cable route 1-3). (Symbols are same as in Fig. 7.)

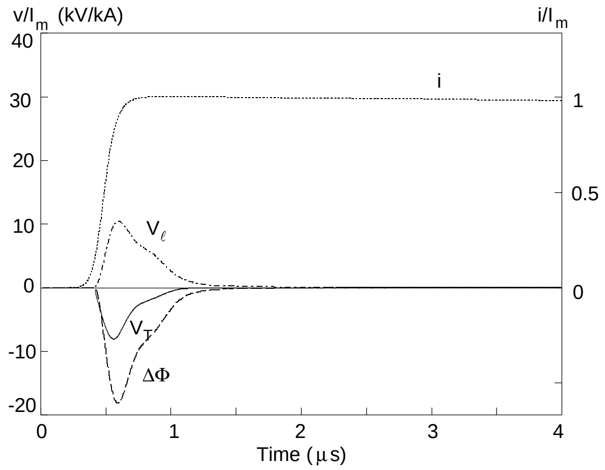


Fig. 9. Influence of lightning current feed-point location on voltage along the shield (cable route 1-2-3): lighting current is injected in the center of the grid. (Symbols are same as in Fig. 7.)

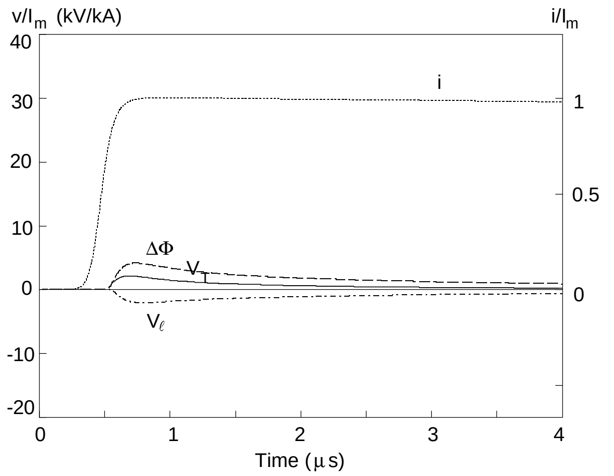


Fig. 10. Influence of soil conductivity on voltage along the shield (cable route 1-2-3): ρ = 100 Ω.m, ε_r = 36. (Symbols are same as in Fig. 7.)

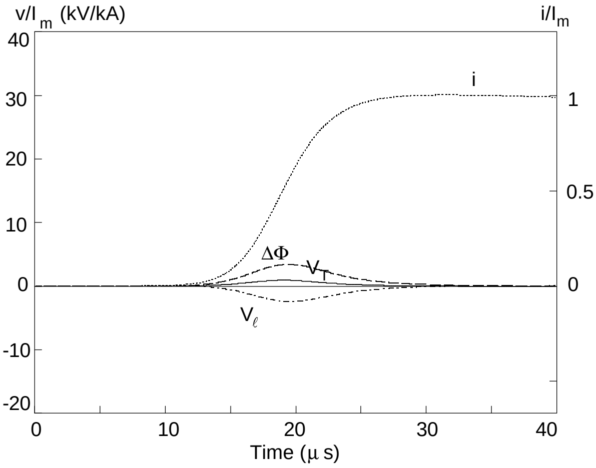


Fig. 11. Influence of lightning current impulse shape on voltage along the shield (cable route 1-2-3): T_1/T_2 = 10/350 μs. (Symbols are same as in Fig. 7.)

smaller that the effective area of the grid. It can be seen in Fig. 13, that among the analyzed cases, only grid with 3 m square meshes, in smaller area near the feed point, substantially reduces the maximal GPR.

Fig. 14 illustrates the possibility to reduce the induced voltage by decrease of the conductor separation in an area near the lightning current feed point. The potential difference component of the voltage is lower, while the field coupling component is maintained high, which results in reduction of the total voltage along the cable shield.

8. CONCLUSIONS

1. A method for computer analysis of transient voltages coupled to shielded cables in HV substations subjected to lightning is presented. The method combines the antenna and circuit theory approaches. Antenna model is used to compute voltages and currents in the shield, while circuit model may be used for evaluation of the voltages coupled to the cables.

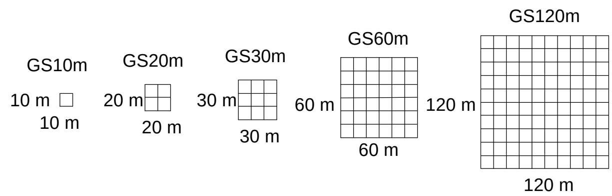
2. Ground potential difference and field coupling components of the voltage along shield are opposite, which results in smaller total voltage than predicted solely on ground potential difference analysis.

3. Greatest influence on the reduction of voltages has factors "beyond control," such as: larger soil conductivity and smaller lightning current impulse steepness.

4. Possibilities to substantially reduce the induced voltages due to the currents in earthing system are:

- smaller earthing conductors separation in the effective area around lightning current feed points,
- cable routes near earthing conductors, and
- shield routes and bonding away from the edge.

5. Presented computer model may be used in analysis of "the worst case" scenario (subsequent stroke, dry soil, corner feed point) and for optimization of the protective measures, concerning the earthing system and the shielding.



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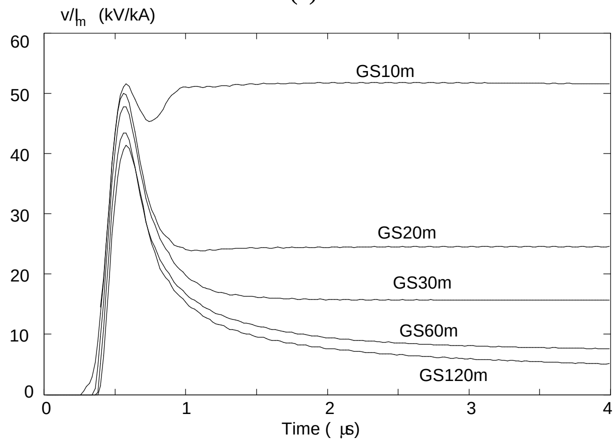
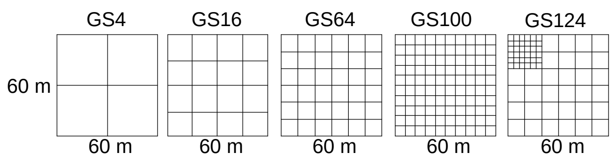


(b)

Fig. 12. Influence of earthing grid size on transient GPR at feed point. Soil is with ρ = 1000 Ω.m and ε_r = 9, and injected current impulse in the corner of the grid with T_1/T_2 = 0.25/100 μs. (a) Analyzed grids. (b) Normalized transient GPR.



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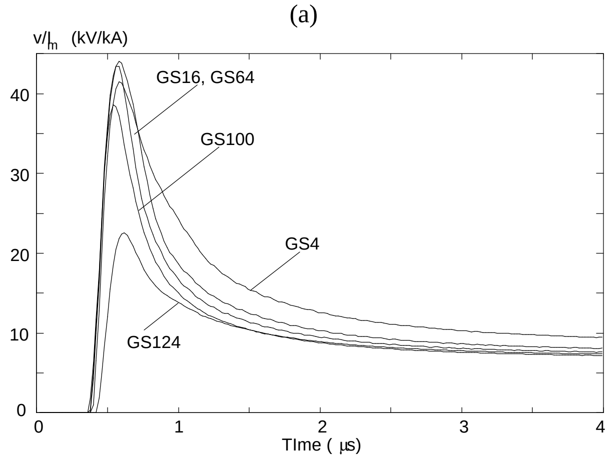

(b)

Fig. 13. Influence of earthing grid conductor separation on transient ground potential rise at feed point. Soil is with ρ = 1000 Ω.m and ε_r = 9, and injected current impulse in the corner of the grid with T_1/T_2 = 0.25/100 μs. (a) Analyzed grids. (b) Normalized transient GPR.

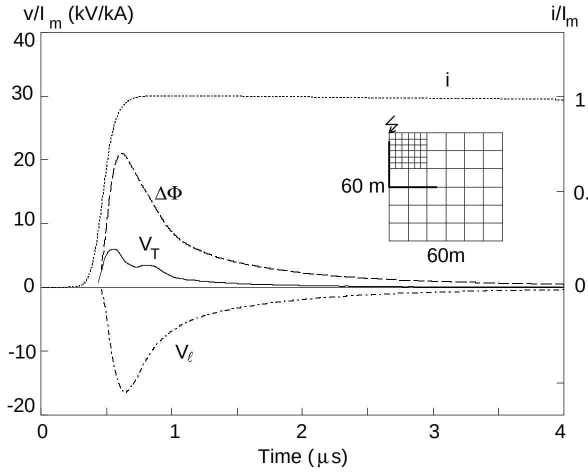

Fig. 14. Influence of earthing grid conductor separation on voltage between points 1 and 3 along the shield. (Symbols are same as in Fig. 8.)

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