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An EMTP Extension for Computing Earthing System Transient Step and Touch Voltages

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SUMMARY

This paper presents a novel technique for computing dangerous voltages due to lightning transients imposed on earthing system, which is based on the use of the well-known ATP-EMTP software package. Earth surface transient potential distributions, as well as step and touch voltages computations, are performed through extending the widely used EMTP software package with a new post-processor (computer program), developed especially for that purpose. The earthing grid is approximated by the circular cross-section conductors. In numerical model, conductors are subdivided into segments (1D finite elements) and Clark's model with distributed constant parameters is then applied. Leakage conductance of conductor segments is modeled in EMTP as an additional lumped parameter. Analytical expressions for distributed and lumped segment parameters are derived using the average potential method. Due to the limitations of the EMTP, EM coupling between segments is neglected. The earth model is limited to the homogenous earth. Soil ionization effect is not accounted for, but could be incorporated, through some modifications of algorithms. Lightning surge model used is based on the Heidler's model of current source.

1. INTRODUCTION

Knowing the transient behavior of the substation's earthing grid is very important in the case of direct lightning strikes. A direct lightning strike can cause dangerous overvoltages, which can result in malfunction of the sensitive equipment, as well as dangerous step and touch voltages. Electromagnetic compatibility issues as well as human safety ones could be investigated using hereafter proposed methods. All parameters necessary for the ATP-EMTP simulations are computed by the separate computer program (pre-processor), developed for that purpose. Earth surface transient potential distribution, as well as touch and step voltages are computed from the simulation results obtained by ATP-EMTP using another computer program (post-processor to the ATP-EMTP).

KEYWORDS

Average potential method, ATP-EMTP, Earthing grid, Lightning analysis, Step and touch voltages

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2. MODEL OF THE EARTHING GRID

Each conductor of the earthing grid, by applying the finite element technique, can be subdivided into segments (1D finite elements). A Clark's model with distributed constant parameters is then applied on each segment. Input data for Clark's model are, [1]: a) resistance per unit length, b) surge impedance, c) propagation velocity, d) segment length.
Additionally, due to the limitations of the ATP-EMTP software package, the leakage conductance (resistance) of buried segments is modeled as an additional lumped parameter, [1].

Ad a) Per unit resistance of earthing grid segment can be computed as follows:

$$R = \frac{\rho_s}{r_o^2 \cdot \pi} \tag{1}$$

where ρ_s is the resistivity of the segment, [Ωm], while r_o represents the equivalent radius of the segment, [m].

Ad b) Surge impedance of the earthing grid segment is defined by the following equation, [4]:

$$Z_s = \sqrt{\frac{L}{C}} = \frac{\sqrt{\varepsilon_o \cdot \varepsilon_r \cdot \mu_o \cdot \mu_r}}{C} \tag{2}$$

where: L – per unit inductance of the segment, [H/m],
C – per unit capacitance of the segment, [F/m],
ε_o – permittivity of the vacuum,
μ_o – permeability of the vacuum,
ε_r – relative permittivity of the earth,
$\mu_r = 1$ – relative permeability of the earth.

Hence, in order to compute the surge impedance, one only needs to obtain the value of per unit capacitance of the earthing grid segment. This capacitance can be computed by the average potential method.
Per unit capacitance of the buried conductor segment depends on the position of the segment respective to the earth surface. It can be computed according to the following expression, [3, 4]:

$$C = \frac{4 \cdot \pi \cdot \varepsilon_o \cdot \varepsilon_r \cdot \ell}{\int\limits_{\Gamma'}\int\limits_{\Gamma} \frac{d\ell' \cdot d\ell}{r} + \int\limits_{\Gamma_s}\int\limits_{\Gamma} \frac{d\ell_s \cdot d\ell}{r}} = \frac{4 \cdot \pi \cdot \varepsilon_o \cdot \varepsilon_r \cdot \ell}{I_{self} + I_{mut}} \tag{3}$$

Double integrals in the above expression are computed analytically, as will be explained later. Integral I_{self} stands for the self capacitance, while integral I_{mut} accounts for the mutual capacitance between earthing grid's segment and its image.

Ad c) Propagation velocity of the lightning surge in the earth can be roughly estimated by the following relation:

$$vp = \frac{c}{\sqrt{\varepsilon_r}} \tag{4}$$

where $c = 3 \cdot 10^8$ m/s represents the velocity of light, and ε_r relative permittivity of the earth.

Ad d) Each of the earthing grid segments should satisfy the following relation for the maximum length, in meters:

$$\ell_{max} = \frac{3160}{6} \cdot \sqrt{\frac{\rho}{f_{max}}} \qquad (5)$$

where ρ is the resistivity of the earth, [Ωm], while f_{max} equals the maximal frequency of interest found in the lightning surge, [Hz].

Leakage conductance of the buried segment is represented in ATP-EMTP with the concentrated resistance on each side of that segment. Double value of the resistance on each side of the segment is chosen ($2 \cdot R_L$) in order to obtain value of R_L after the parallel connection. Value of the earthing grid conductor's resistance is composed of two terms, as follows, [3, 4]:

$$R_L = \frac{\rho}{4 \cdot \pi \cdot \ell^2} \cdot \left(\int_{\Gamma'} \int_{\Gamma} \frac{d\ell' \cdot d\ell}{r} + \int_{\Gamma_s} \int_{\Gamma} \frac{d\ell_s \cdot d\ell}{r} \right) = \frac{\rho}{4 \cdot \pi \cdot \ell^2} \cdot \left(I_{self} + I_{mut} \right) = R_{self} + R_{mut} \qquad (6)$$

where: R_{self} - self resistance of the segment in homogeneous and unbounded medium (earth),

R_{mut} - mutual resistance between segment and its image in relation to the earth surface.

Double integrals (I_{self} for the self resistance and I_{mut} for mutual resistance) are those already introduced. They are analytically computed.

2.1 Analytical Solution of Double Integrals

Expressions for computing per unit capacitance of earthing grid segments, and resistance (conductance) of earthing grid segments all involve double integrals. They can be analytically solved which contributes to the numerical stability of the derived method.

Double integral I_{self} is given by the expression:

$$I_{self} = \int_{\Gamma'} \int_{\Gamma} \frac{d\ell' \cdot d\ell}{r} \qquad (7)$$

The integration in equation (7) is performed along the segment axis (curve Γ') and along the curve on segment surface, which is parallel to the segment axis (curve Γ). Analytical solution of this integral is given by the following expression, [3, 4]:

$$I_{self} = 2 \cdot \left(\ell \cdot \ln \frac{\sqrt{\ell^2 + r_o^2} + \ell}{r_o} - \sqrt{\ell^2 + r_o^2} + r_o \right) \qquad (8)$$

where ℓ represents segment's length, while r_o represents equivalent radius of the segment's cross-section.

Double integral I_{mut} is given by the following expression:

$$I_{mut} = \int_{\Gamma_s} \int_{\Gamma} \frac{d\ell_s \cdot d\ell}{r} \qquad (9)$$

Analytical solution of integral (9) depends on the position of the segment relative to the earth surface. Three different segment arrangements will be examined: a) segment is parallel to the earth surface, b) segment is perpendicular to the earth surface, c) segment is in an aslope position to the earth surface.

Ad a) If a horizontal segment is positioned at distance h [m] parallel to the earth surface, integral solution is ($r_o \rightarrow 2 \cdot h \;\; \Rightarrow \;\; I_{self} \rightarrow I_{mut}$):

$$I_{mut} = 2 \cdot \left(\ell \cdot \ln \frac{\sqrt{\ell^2 + 4 \cdot h^2} + \ell}{2 \cdot h} - \sqrt{\ell^2 + 4 \cdot h^2} + 2 \cdot h \right) \qquad (10)$$

Ad b) If the segment is perpendicular to the earth surface, the first integration in (9) is carried out along the axis of segment image (curve Γ_s), while the second integration is carried out along the curve on the segment surface (curve Γ), which is parallel to the segment axis. Analytical solution to the integral (9) in this case is given by [3, 4]:

$$I_{mut} = u_1 \cdot \mathrm{Arsh} \frac{u_1}{r_o} - \sqrt{u_1^2 + r_o^2} + u_2 \cdot \mathrm{Arsh} \frac{u_2}{r_o} - \sqrt{u_2^2 + r_o^2} - 2 \cdot u_3 \cdot \mathrm{Arsh} \frac{u_3}{r_o} + \sqrt{u_3^2 + r_o^2} \qquad (11)$$

with:

$$u_1 = h_1 + h_2 + \ell \qquad (12)$$

$$u_2 = h_1 + h_2 - \ell \qquad (13)$$

$$u_3 = h_1 + h_2 \qquad (14)$$

where h_1 and h_2 represents distances of the starting and ending points of the segment from the earth surface, respectively.

Ad c) If the segment is in an aslope position relative to the earth surface, analytical solution of the double integral can be written as [3, 4]:

$$I_{mut} = 2 \cdot \left[B(x_p, z_p) + B(x_k, z_k) - B(x_p, z_k) - B(x_k, z_p) \right] \qquad (15)$$

where x_p, z_p, x_k and z_k represent x and z coordinates of the starting and ending points of the segment and its image, respectively. Terms in (15) are computed using the following expression, [3, 4]:

$$B(x, z) = x \cdot \ln \left(z - x \cdot \cos\alpha + \sqrt{x^2 + z^2 + r_o^2 - 2 \cdot x \cdot z \cdot \cos\alpha} \right) \qquad (16)$$

with:

$$x_p = z_p = \frac{\min\{h_1, h_2\}}{|h_2 - h_1|} \cdot \ell \qquad (17)$$

$$x_k = z_k = \frac{\max\{h_1, h_2\}}{|h_2 - h_1|} \cdot \ell \qquad (18)$$

$$\cos\alpha = \frac{2 \cdot d^2}{\mathbf{l}^2} - 1 \qquad (19)$$

where d represents the length of the orthogonal projection of the segment onto the earth surface. Length of the segment can be obtained using the following expression:

$$\ell = \sqrt{d^2 + (h_2 - h_1)^2} \qquad (20)$$

3. EARTH SURFACE POTENTIAL DISTRIBUTION

ATP-EMTP software package applied for the simulations can only give transient potential distribution on the earthing grid itself (in the nodes between segments). More important is an earth surface potential distribution from which step and touch voltages could be computed. In order to overcome this disability of the ATP-EMTP, a separate post-processor (computer program) has been developed.
From inside the ATP-EMTP, user can request to publish (within results) a leakage currents which each of the earthing grid conductors dissipate into the earth. This is a current flowing through the lumped resistances, which represent the leakage resistance of the buried conductor segment. From this current, an earth surface transient potential distribution can be computed. Knowing the earth surface potential distribution, step and touch voltages could be easily obtained.
Figure 1 shows a single buried conductor segment in a local coordinate system, along with the point T(u, v) for which the potential needs to be computed.

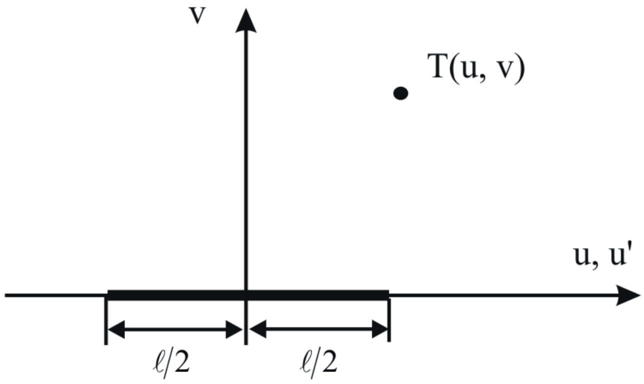


Figure 1. Earthing grid segment in local coordinate system (u, v).

Potential at the point T(u, v) at the time instant t as a consequence of the current I(t), which the segment in the unbounded homogenous medium with resistivity ρ dissipates into the earth, can be computed according to the following expression:

$$\varphi_T(t) = \frac{\rho}{4\cdot\pi}\cdot\frac{I\left(t - \frac{r_s}{vp}\right)}{l}\cdot G(u, v) \tag{21}$$

where u and v are local coordinates of the point T(u, v), r_s - distance in the local coordinate system from the middle segment point to the observation point T(u, v). Length of the segment is given by ℓ, while vp stands for the velocity of the surge current in the earth, given by (4). Term expressing the current in the above expression accounts for the potential retardation. Function G(u, v) in (21) depends on the geometry of the segment and the position of the observation point. It is given by, [7]:

$$G(u, v) = \int_{-l/2}^{l/2} \frac{du'}{\sqrt{(u-u')^2 + v^2}} = \ln \frac{\sqrt{\left(u+\frac{l}{2}\right)^2 + v^2} + u + \frac{l}{2}}{\sqrt{\left(u-\frac{l}{2}\right)^2 + v^2} + u - \frac{l}{2}} \tag{22}$$

Local coordinates of the point T(u, v) can be computed from the global coordinates of the segment starting and ending points and global coordinates of the observation point. Let the starting point of the segment be $P(x_p, y_p, z_p)$, and ending point of the same segment $K(x_k, y_k, z_k)$, and let's designate observation point as T(x, y, z) in the global coordinate system. Origin of the local coordinate system is in the middle segment point with global coordinates $S(x_s, y_s, z_s)$. Distance between the middle segment point and the observation point (expressed with global coordinates) is given by the following expression, [7]:

$$r_s = \sqrt{(x_s - x)^2 + (y_s - y)^2 + (z_s - z)^2} \tag{23}$$

Local coordinates u and v of the observation point can be computed as follows, [7]:

$$u = \frac{2}{l} \cdot \left[(x - x_s) \cdot (x_k - x_s) + (y - y_s) \cdot (y_k - y_s) + (z - z_s) \cdot (z_k - z_s) \right] \tag{24}$$

$$v = \sqrt{(x - x_s)^2 + (y - y_s)^2 + (z - z_s)^2 - u^2} \tag{25}$$

where the length ℓ of the segment can be computed as follows:

$$l = \sqrt{(x_k - x_p)^2 + (y_k - y_p)^2 + (z_k - z_p)^2} \tag{26}$$

Potential at the observation point T on the earth surface, which is a consequence of leakage currents of N arbitrarily positioned (mutually connected) earthing grid conductors can be computed by the following expression:

$$\varphi_T(t) = \frac{\rho}{2 \cdot \pi} \cdot \sum_{k=1}^{N} \frac{I_k\left(t - \frac{r_{sk}}{vp}\right)}{l_k} \cdot G_k(u, v) \tag{27}$$

where: ℓ_k – length of the k-th segment, computed according to (26), [m],

$G_k(u, v)$ – function joined to the k-th segment, described by (22),

$I_k\left(t - \frac{r_{sk}}{vp}\right)$ – leakage current of the k-th segment with potential retardation, [A].

Discret values of the leakage currents I_k as a function of time without potential retardation are obtained from the ATP-EMTP output. For each time instant, satisfying the following inequality:

$$t_m \le t - \frac{r_{sk}}{vp} \le t_{m+1} \tag{28}$$

current I_k of the k-th segment as a function of time with potential retardation is given by the following expression:

$$I_k\left(t - \frac{r_{sk}}{vp}\right) = (1 - f_{km}) \cdot I_k(t_m) + f_{km} \cdot I_k(t_{m+1}) \tag{29}$$

where:

$$f_{km} = \frac{t - \frac{r_{sk}}{vp} - t_m}{t_{m+1} - t_m} \tag{30}$$

Thus, according to (29), it can be seen that the current of the k-th segment is linearly approximated between the two successive time-discret values obtained from ATP-EMTP output.
Function $G_k(u, v)$ depends on the position of the k-th segment in the global coordinate system and can be computed according to relation (22). Thus, a potential at the observation point on the earth surface at the time instant t is computed by summing the contributions from all the conductors, and their images, taking into account the potential retardation at the same time. In this way, transient temporal and spatial potential distributions on the earth surface can be computed. From those values, step and touch voltages could be easily obtained. In order to carry out these computations, separate computer program (post-processor to the ATP-EMTP) has been developed.

4. NUMERICAL EXAMPLE

Figure 2 illustrates the problem analysed in this paper. It consists of a 60 m x 60 m square grid with 10 m x 10 m meshes buried at depth of 0.5 m. The grid is made of copper conductors with 5 mm radius. The soil is assumed to be homogenous with a 1000 Ωm resistivity, relative permittivity of 9 and relative permeability of 1. Lightning surge current with following parameters: 1000 A amplitude and 1/20 μs shape has been injected in the lower left corner of the earthing grid. Lightning surge model used for the ATP-EMTP simulation is based on the Heidler's model of current source, [1].

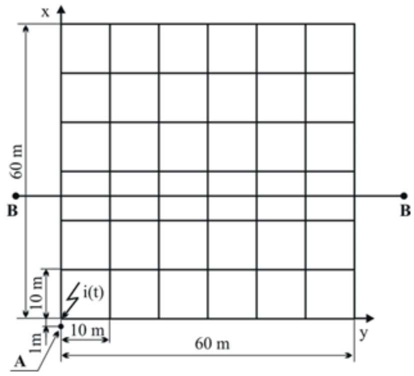


Figure 2. A earthing grid subject to a lightning strike

Observation point for the computation of the transient touch voltage is also shown in the Figure 2 (point A). Touch voltage between this point, located 1 m from the metallic structure at global coordinates (-1; 0; 0), which could be touched, is computed. Single profile on the earth surface has also been selected in order to compute the transient step voltage distribution (profile B–B in the Figure 2). This profile starts at the following global coordinates: (25; -10; 0) and extends to the point with global coordinates (25; 70; 0).

Complete model of the earthing grid presented in Figure 2 has been constructed in ATP-EMTP software package. Parameters of earthing grid elements have been previously computed by means of a separate computer program (pre-processor), according to the above presented model equations. Transient earth surface potential distribution, transient touch and step voltages have been computed from the leakage current distribution obtained from ATP-EMTP by means of specially developed post-processor.

Figure 3 presents two "screen-captures" from the post-processor animation showing a 3D perspective of the transient earth surface potential distribution over the earthing grid at two distinct time instants: t = 0.5 μs at the left portion and t = 5 μs at the right. Computations were carried out at various observation points located on the earth surface along several Y-directed profiles covering the earth grid and its vicinity, i.e. 10 m outside the grid outer loop.

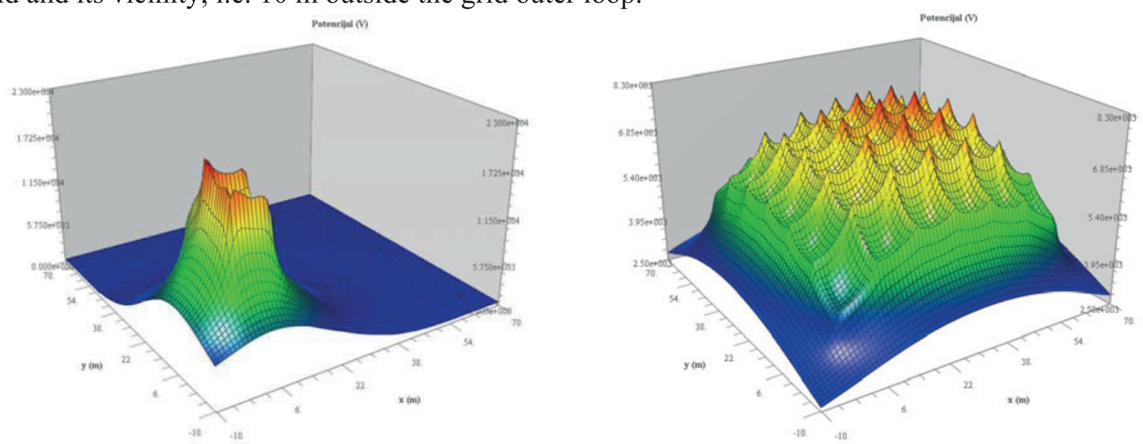
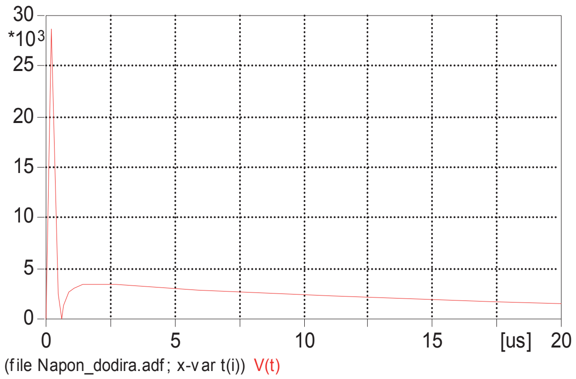


Figure 3. 3D perspectives of transient earth surface potential distribution for two distinct time instants (on the left: t = 0.5 μs, and on the right: t = 5 μs).

Amplitude of the transient voltage (z axis) on the left portion of Figure 3 approximates to 23 kV, while on the right portion of Figure 3 it is approximately 8.3 kV.
Figure 4 presents on the left portion a transient touch voltage at the observation point A defined in Figure 2. At the right portion of the Figure 4, a transient step voltage along profile B–B for the time instant t = 10 μs is presented. This profile has been defined in the Figure 2 as well.



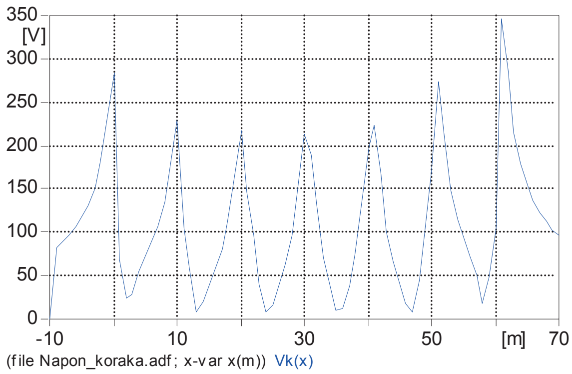


Figure 4. Transient touch voltage at the observation point A (on the left), and transient step voltage along profile B–B at the time instant t = 10 μs (on the right).

5. CONCLUSION

Advantage of the presented TLM based approach for transient step and touch voltages computation is its relative simplicity, and acknowledged good agreement [4] with results obtained from more complex EM fields theory based models.
Earth surface transient potential distributions, as well as step and touch voltages computations, are performed through extending the well-known ATP-EMTP software package with a new post-processor (computer program), developed especially for that purpose.
Due to the limitations of the applied transmission line model approach and the application of the ATP-EMTP software package, electromagnetic coupling between segments could not be taken into account. The earth model is limited to the homogenous earth. Soil ionization effect is not accounted for here.

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