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POWER SYSTEMS AND POWER ELECTRONICS

Influence of lightning current surge shape and peak value on grounding parameters

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Abstract. Groundings are necessary parts included in lightning and shock protection. In the case of a surge current, high current phenomena are observed inside the grounding. They are a result of the electrical discharges around the electrode when the critical field is exceeded in soil. An available mathematical model of grounding was used to conduct computer simulations and to evaluate the influence of current peak value on horizontal grounding parameters in two cases. In the first simulations, electrodes placed in two different soils were considered. The second case was a test of the influence of current peak value on grounding electrodes of various lengths. Simulation results show that as soil resistivity increases in value, the surge impedance to static resistance ratio decreases. In the case of grounding electrodes lengths, it was confirmed that there is a need to use an operating parameter named effective grounding electrode length, because when it is exceeded, the characteristics of grounding are not significantly improved during conductance of lightning surges. The mathematical model used in the paper was verified in a comparison with laboratory tests conducted by K.S. Stiefanow and with mathematical model described by L. Grcev.

Key words: grounding electrodes; grounding impedance; grounding coefficient; transient response.

1. Introduction

Groundings are characterized by different qualities of current transmission. All these qualities depend on the kind of current. Currents may be considered low-frequency or in the case of lightning current as a surge. In the first case, groundings are characterized by static impedance. The second kind of currents is mostly described by the parameter named surge impedance [1].

Groundings' surge qualities are remarkably important in the lightning protection of buildings, electrical devices, and objects in power transmission systems. Voltage drop on groundings' electrodes during surge current flow with high peak value is described by a nonlinear function. The soil ionization phenomenon around the metal electrode and its inductance have a crucial influence on grounding parameters. A stroke of cloud-to-facility lightning should implicate surge current dispersion by grounding electrodes. In some cases, even in buildings with lightning protection systems, a portion of surge current gets to electrical objects or telecommunication installations. The presence of this phenomenon puts the life and health of people inside such buildings in danger throughout the tempest's duration. Lightning surges may also lead to permanent malfunctions of electrical and electronic devices.

The flow of lightning surge current in grounding electrodes is linked to notable voltage drop on them. This has an important impact on the durability of an installation's insulation. Another effect of lightning current is the potential difference between the soil surface and metal structures of objects, installations, and devices. This effect increases the possibility of being shocked by step or touch voltage. Among other consequences, the risk of fire or explosion may be considered (especially in Ex-zones) [2, 3].

The effects of lightning surges, mentioned in the previous paragraph, force the right actions during the designing and construction phases of lightning protection systems. The grounding, properly built, has the influence on the installation and devices safety in the case of direct or close lightning strike. These values of surges locally injected into the power grid are dependent on the parameters and overall structure of the grounding system.

During the storm season, facility owners may suffer substantial financial losses due to improperly built lightning protection installations. Such losses are mostly the result of a break in power delivery and malfunctions of electrical/electronic devices. This is often the result of an incorrect understanding of the lightning protection's system utility at the moment of a lightning strike. Proper knowledge about the complicated phenomena observed during surge current flow in the grounding electrode and soil surrounding the rod is an opportunity for scientists and engineers [4]. They have a chance to prepare a simulation model and make efficient and effective lightning protection systems based on simulation model [5].

This paper presents the influence of surge current parameters and especially its peak value on grounding parameters. Results are presented for grounding surge impedance and grounding surge impedance coefficient. Current surges were modelled

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as 4/10 µs/µs. The simulation was realized in PSpice software. The prepared model was compared to experimental results obtained by K.S. Stiefanow [6] and to the simplified model proposed by L. Grcev [7].

2. Introduction

The existing grounding model was compared with the literature data and L. Grcev's dependencies. It was demonstrated that the relative error between the tests and simulations results is noticeably larger in contradiction to Grcev's publications.

The influence of the surge current peak value on the grounding surge impedance and the grounding surge impedance coefficient was proved. Relevant relationships were elaborated and results discussed regarding the impact of surge current peak value on the grounding parameters.

3. Horizontal electrode grounding model

3.1. Grounding model parameters. The electrical parameters of a grounding are dependent on its configuration (shape and position of metal electrode placed in the soil) and soil properties. Grounding is characterized by the material's resistance (mostly it is steel or copper) and inductance. Current flow in the grounding is bounded with inductive and conductive effects.

The inductance L of the electrode, as a first parameter, may be expressed, in H, by formula [8, 9]:

$$L = \frac{\mu}{2\pi}\left[\log\frac{2l}{r} - 1\right], \tag{1}$$

where l (in m) is the electrode's length, r (in m) is the metal rod's radius, and μ is the soil's permeability in (H/m).

The value of resistance per unit length R in Ω/m may be calculated according to the following formula:

$$R' = \frac{1}{\gamma P}, \tag{2}$$

where γ (in S/m) is the conductivity of the material of the rod, which is placed in the soil as the grounding, P (in m^2) is the cross-sectional area of the electrode. The conductivity of the steel is equal: $\gamma_{\mathrm{Fe}} = 8,33\cdot 10^6$ S/m. For copper, the value is: $\gamma_{\mathrm{Cu}} = 55\cdot 10^6$ S/m.

During lightning current flows through a grounding electrode, the influence of current peak value on resistance per unit length R' is negligibly small. This feature is due to the voltage drop ΔU_R across the resistance R in comparison to the voltage drop ΔU_L across the inductance L is negligible.

Capacity per unit length of the horizontal electrode for low-frequency currents, in pF/m, can be calculated from the following formula [8, 9]:

$$C' = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln\dfrac{2H}{r_0}} = \frac{55\varepsilon_r}{\ln\dfrac{2H}{r_0}}, \tag{3}$$

where ε_r is relative permittivity of soil, $\varepsilon_0 = 8.85\cdot 10^{-12}$ F/m is vacuum permittivity of soil, H (in m) is the distance between the electrode and the soil surface of the area where electrical field vector is equal zero, and r_0 (in m) is the grounding electrode's radius.

The model must include the presence of electrical discharges in soil and zones of spark implicated by high-current phenomenon. In this case, electrode radius r_0 has to be replaced by radius r_x (in m). It can be calculated by the following formula [8, 9]:

$$r_x = \frac{\rho I_m}{2\pi l E_k}, \tag{4}$$

where ρ (in Ωm) is a soil resistivity, I_m (in kA) is the peak value of lightning current, l (in m) is grounding electrode length, E_k (in kV/m) is critical electric field value. Mathematical formula (4) has to be applied when the following condition is true:

$$r_0 < r_x. \tag{5}$$

In other cases, radius r_x of grounding ionized space is equal to the metal electrode radius r_0:

$$r_0 = r_x. \tag{6}$$

Static conductance of vertical grounding electrode per unit length G in S/m is based on the formula calculated for the average potential method. It is presented in mathematical form [6]:

$$G' = \frac{2\pi}{\rho\ln\dfrac{l}{r_0}}. \tag{7}$$

Static conductance of horizontal grounding electrode per unit length G' (in S/m) is described by the formula [6]:

$$G' = \frac{2\pi}{\rho\ln\dfrac{l^2}{Hr_0}}. \tag{8}$$

Values for grounding conductance per unit during lightning current flow are calculated by (7) and (8). The only difference in the case when the presence of electrical discharges is observed inside the soil, where grounding electrode radius r_0 is replaced by radius r_x, mathematically expressed by (4).

In publications [8, 10–23], many different concepts of grounding models for surge current conditions are presented. In this paper, the simplified model is considered, where constant radius r_x of the grounding ionized space is assumed for the electrode's entire length. The main idea of the assumption is presented for a vertical electrode structure in Fig. 1.

During the grounding modelling process, it is necessary to replace the model with clustered parameters with the model with parameters per unit length. This allows for observation of phenomena bounded by the grounding's effective length during lightning surge current transmission. The model has the structure of a limited number of segments s per length l. A diagram for a single grounding model segment is illustrated in Fig. 2.

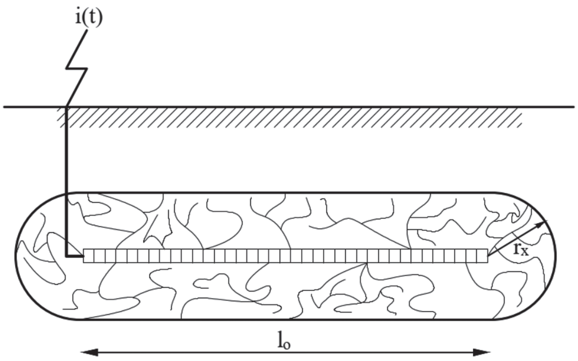

Fig. 1. Example of the zone of electrical dischanges (ionization zone) inside the soil arround the horizontal grounding electrode [16, 18]

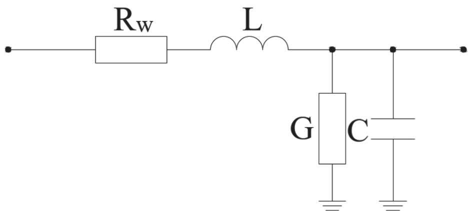

Fig. 2. Single segment of the grounding model; R_w is a segment metal electrode resistance; G is soil segment conductance, L is segment grounding inductance, and C is grounding segment capacity [18,21,24]

The length of a single segment Δl is calculated by the formula:

$$\Delta l = \frac{l}{s}. \tag{9}$$

Parameters per length for resistance R, conductance G, and capacity C are calculated by (2), (3), (6), and (7). Calculations of clustered parameters for a single segment are based on multiplication of the previously mentioned values by its length Δl. To find inductance per length, (1) has to be divided by (9). Electrode segment resistance R_w, soil segment conductance G, and segment inductivity L, segment capacity C are calculated by the following formulas:

$$R_w = R'\Delta l\,, \tag{10}$$

$$G = G'\Delta l\,, \tag{11}$$

$$L = L'\Delta l\,, \tag{12}$$

$$C = C'\Delta l\,. \tag{13}$$

3.2. Lightning current model. Work on shapes of recorded lightning surges led to their mathematical description. Different equations are available in various publications. Nowadays, one of the most popular, is the definition proposed by F. Heidler [25]:

$$i(t) = \frac{I_m}{k}\cdot\frac{\left(\frac{t}{\tau_1}\right)^n}{1+\left(\frac{t}{\tau_1}\right)^n}\cdot\exp\left(-\frac{t}{\tau_2}\right), \tag{14}$$

where I_m (in A) is peak current value, τ_1 (in s) is the time constant modelling the front time of current surge, τ_2 (in s) is the time constant modelling the tail time of current surge, k is correction coefficient of function maximum value, n is an exponent, being a real number within the range from 2 to 10.

Lightning current surge given by F. Heidler's function requires knowledge of a few parameters [26]. The needed values are the time constant of front time T_1, the time constant of tail time T_2, and the peak current I_m.

Having the aforementioned parameters, the only missing data are values of correction coefficient k and exponent n. On the basis of known time constants, it is possible to identify the proper value of exponent n. It is important to emphasize that, current I_m and correction coefficient k have an influence only on the scaling of (14), and the times of characteristics values of $i(t)$ remain constant. Exponent n is a real number within the range from 2 to 10. This parameter is determined empirically. Identification is based on the representation of curves (14) in the coordinate system for the chosen exponent. The current axis should be scaled in percentages or in the per-unit system.

The first step of identifying correction coefficient k is calculation of the time t_{I_m}, at which lightning current $i(t)$ reaches its maximum value. Time t_{I_m} is calculated by the derivative of the function $\mathrm{d}i/\mathrm{d}t$:

$$\frac{\mathrm{d}i}{\mathrm{d}t} = \frac{I_m}{k}\cdot\frac{\left(\frac{t}{\tau_1}\right)^n}{1+\left(\frac{t}{\tau_1}\right)^n}\cdot\frac{1}{\tau_1}\cdot\exp\left(-\frac{t}{\tau_2}\right) \cdot\left(\frac{n}{1+\left(\frac{t}{\tau_1}\right)^n}-\frac{t}{\tau_2}\right). \tag{15}$$

According to the principles of mathematical analysis, the maximum or minimum of a function $f(t)$ exists when the derivative $\mathrm{d}f/\mathrm{d}t$ meets the condition:

$$\frac{\mathrm{d}f}{\mathrm{d}t} = 0. \tag{16}$$

In the considered case, for lightning current $i(t)$, the relationship defined as follows must be fulfilled:

$$\frac{\mathrm{d}i}{\mathrm{d}t} = 0. \tag{17}$$

The combination of (15) and (17) yields the following equation:

$$\frac{n}{1+\left(\frac{t}{\tau_1}\right)^n}-\frac{t}{\tau_2} = 0. \tag{18}$$

After the appropriate algebraic transformation, (18) obtains the form:

$$t^{n+1} + \tau_1^n t - n\tau_1^n\tau_2 = 0. \tag{19}$$

The solution of polynomial (19) is the sought value of time t_{I_m}, for which function $i(t)$ has a maximum value of the lightning surge current. It is important to emphasize that (19) should be easily solved by numerical applications.

When time t_{I_m} is known, it is possible to compute the value of correction coefficient k. Mathematically, the condition is represented by the following equation:

$$i\left(t_{I_m}\right) = I_m\,. \tag{20}$$

Finally, the equation used to find the value of correction coefficient k has the formula:

$$k = \frac{\left(\frac{t_{I_m}}{\tau_1}\right)^n}{1+\left(\frac{t_{I_m}}{\tau_1}\right)^n} \cdot \exp\left(-\frac{t_{I_m}}{\tau_2}\right). \tag{21}$$

In the case where time tail T_2 is a few times (two times/three times) greater than front time T_1, time constants τ_1 and τ_2 of F. Heidler's function are calculated by a different method than the one presented in the paper. An example of such lightning current surge is when the front time is equal to $T_1 = 4$ µs and tail time has a value of $T_2 = 10$ µs. The first step is based on defining exponent n. The next one is to empirically fit time constants τ_1 and τ_2 in a way which finally give the desired shape of the lightning current. Verification of the front time, tail time, and correction coefficient is based on the rules described in the previous paragraphs. Table 1 compiles parameters used in (14).

Table 1
Example of the parameters of (14) [27]

Parameter	200 kA 10/350 µs	100 kA 1/200 µs	50 kA 0.25/100 µs	20 kA 2/50 µs
Correction coefficient k	0.930	0.986	0.993	0.903
Time constant τ_1	19	1.82	0.454	3.867
Time constant τ_2	485	285	143	66.507
Exponent n	10	10	10	10

3.3. Grounding simulation model in PSpice. During the process of preparing the simulation, it is necessary to define the number of segments used to model the qualities of the grounding structure expressed by its conductance and inductance. From the practical point of view, the limited number of segments is directly connected to optimization of the time needed to carry out numerical calculations. Other conditions are dependent on the software version. For instance, in PSpice student edition, circuit models may be built with 64 elements (e.g., resistances, inductances, etc.) [28]. The model used for the purposes of this paper is built out of 10 segments ($s = 10$). Parameters for each circuit element of the model were determined by the formulas presented in the previous part of the paper. A part of the prepared simulation's structure is shown in Fig. 3.

One of the problems with PSpice is the implementation of the current source. Function (14) may be added to the simulation as

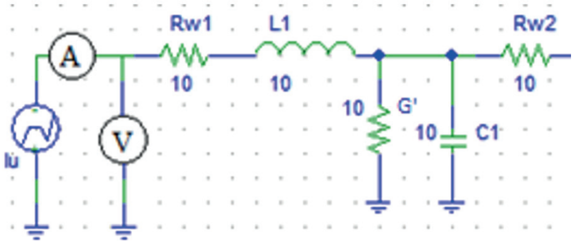

Fig. 3. A part of the grounding model implemented in PSpice software with marked places of the measured voltage (V) and current (A) values needed to calculate parameters during ligtning current flow; Iu is a current peak value source

a nonstandard source named IPWL_FILE. It generates a signal based on linear approximation. In this case, the data source is a text file with discretized values of time and current. A constant step, defined by the simulation creator, is kept between the two values.

4. Grounding surge impedance coefficient

4.1. Grounding model coefficient formula. Grounding resistance or impedance is characterized by dynamic features. It changes over time and it is a nonlinear function.

For complex grounding systems with long lengths, inductance has an important influence on surge parameter. This is the consequence of the fact that a lightning current surge is characterized by front time. The presence of grounding inductance makes the impedance function more nonlinear in the time domain.

In technical applications, the correlation between maximum voltage drop value U_m on the grounding electrode and the maximum value of current I_m have much greater practical significance. During current flow, a time shift between the occurrence of U_m and I_m is always observed. This correlation is described in publications as grounding surge impedance Z_u [10]:

$$Z_u = \frac{U_m}{I_m}\,. \tag{22}$$

Another important parameter is the coefficient representing boundaries between the value of surge impedance Z_u and static resistance R_{stat}. This factor is called the grounding surge impedance coefficient. The specific value for the grounding may be identified by the results of computer simulations, experimental records or analytical estimation. Surge impedance coefficient A is defined by the formula [9]:

$$A = \frac{Z_u}{R_{\text{stat}}}\,. \tag{23}$$

4.2. L. Grcev's method of calculating surge impedance coefficient. An analytical method was proposed by L. Grcev in [7], and it is based on experimental results. The calculation scheme is bounded by the parameter called effective length l_{eff} [17]:

$$l_{\text{eff}} = \frac{1-\beta}{\alpha}. \tag{24}$$

Coefficients α and β are represented by the following formula [7]:

$$\alpha = 0.025 + e^{-0.82\cdot(\rho T_1)^{0.257}}, \tag{25}$$

$$\beta = 0.170 + e^{-0.22\cdot(\rho T_1)^{0.555}}. \tag{26}$$

When electrode length is less than or equal to l_{eff}, then surge impedance coefficient A_0 is equal to [7]:

$$A_0 = 1 \quad (l \le l_{\text{eff}}). \tag{27}$$

In other cases, it has the form [7]:

$$A_0 = \alpha l + \beta \quad (l \ge l_{\text{eff}}). \tag{28}$$

The influence of ionization should be included when the maximum value of current I_m is much higher than the value of current I_g which initiates electrical discharges in the soil [7]:

$$I_m \gg I_g. \tag{29}$$

Current I_g is approximated by the formula [7]:

$$I_g = \frac{E_k \rho}{2\pi R_{\text{stat}}^2}. \tag{30}$$

Static resistance for a vertical electrode is calculated by [24]:

$$R_{\text{stat}} = \frac{\rho}{\pi l}\left[\ln\left(\frac{2l}{\sqrt{2r_0 H}}\right) - 1\right]. \tag{31}$$

Static resistance for a horizontal electrode is calculated by [24]:

$$R_{\text{stat}} = \frac{\rho}{2\pi l}\left[\ln\left(\frac{4l}{r_0}\right) - 1\right]. \tag{32}$$

When condition (29) is met, coefficient A is equal to [7]:

$$A = A_0 - 1 + \frac{1}{\sqrt{1+\frac{I_m}{I_g}}}. \tag{33}$$

In other cases, the following form is true [7]:

$$A = A_0. \tag{34}$$

5. Simulation and calculation results

The first of the conducted tests concerns the influence of current peak value on the surge impedance coefficient of horizontal grounding electrodes placed in soils with different resistivity ρ (equal to 40 Ωm and 200 Ωm). Other parameters: length $l = 5$ m, intensity of electric field initiating discharges in the soil $E_k = 300$ kV/m, soil's relative dielectric permittivity $\varepsilon_r = 8$, depth of the grounding electrode's placement $H = 1$ m, and radius of the electrode's cross-section $r_0 = 6$ mm are identical for both analysed cases. Surge current shape parameters are equal to $T_1 = 4$ µs and $T_2 = 10$ µs. Simulation results are presented as a diagram in Figs. 4 and 5.

Analysis of simulation calculations leads to the conclusion, that for lower soil resistivity, the grounding electrode's impact

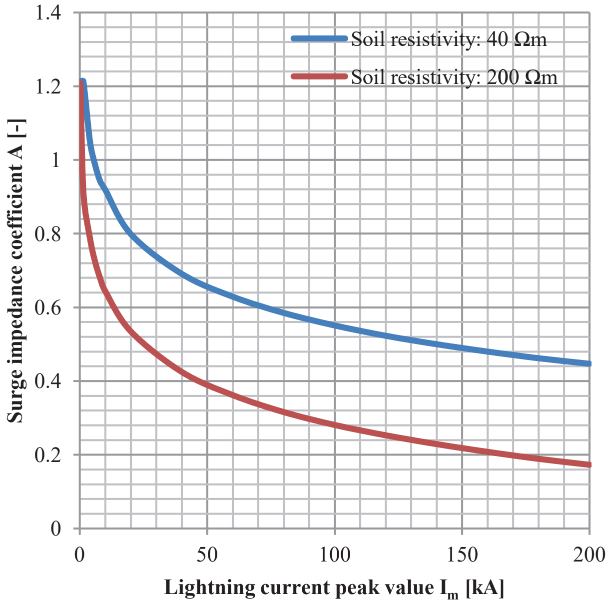

Fig. 4. Grounding surge impedance coefficient for different values of the lightning current peak value for identical grounding electrodes placed in soils characterized by different resistivities equal to 40 Ωm and 200 Ωm

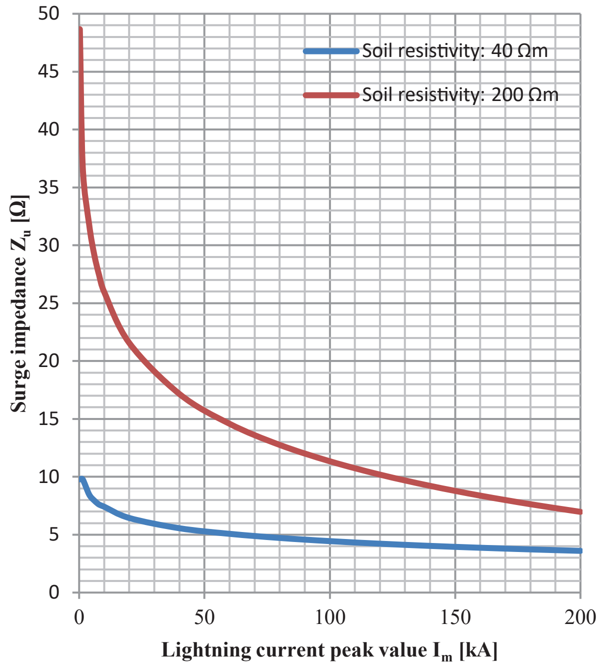

Fig. 5. Grounding surge impedance for different values of the lightning current peak value for identical grounding electrodes placed in soils characterized by different resistivities equal to 40 Ωm and 200 Ωm

features are more preferable. Surge impedance is lower, which has a positive influence on the efficiency of lightning current transmission. Current peak value rises for soil with the resistivity of 200 Ωm. The increase of the current peak value makes the surge impedance, for the soil with a resistivity of 40 Ωm. Changes of the surge impedance coefficient derivative $\mathrm{d}A/\mathrm{d}I_m$ and the surge impedance derivative $\mathrm{d}Z_u/\mathrm{d}I_m$ are higher for the soil with the resistivity of 200 Ωm than for the soil with the resistivity of 40 Ωm.

The second of the conducted tests concerns the influence of current peak value on the surge impedance coefficient of horizontal grounding electrodes with different lengths h (equal 5 m and 20 m) placed in soils. Other parameters: soil resistivity $\rho = 40$ *Omega*m, intensity of electric field initiating discharges in the soil $E_k = 300$ kV/m, soil's relative dielectric permittivity $\varepsilon_r = 8$, depth of the grounding electrode's placement $H = 1$ m and radius of the electrode's cross-section $r_0 = 6$ mm are identical for both analyzed cases. Surge current shape parameters are equal to $T_1 = 4$ µs and $T_2 = 10$ µs. Simulation results are presented as a diagram in Figs. 6 and 7.

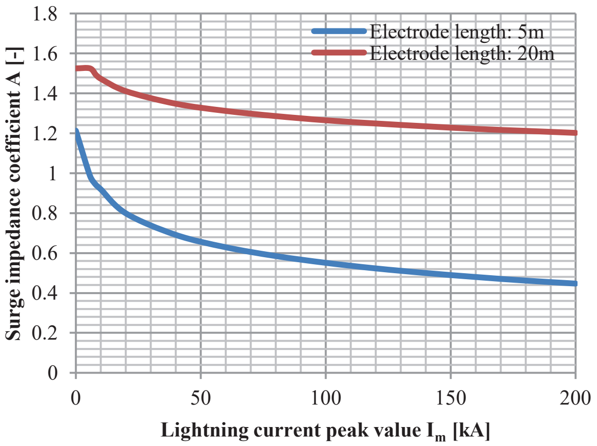

Fig. 6. Grounding surge impedance for different values of the lightning current peak value for differnet grounding electrodes with lenghts equal to 5 m and 10 m, placed in an identical soil

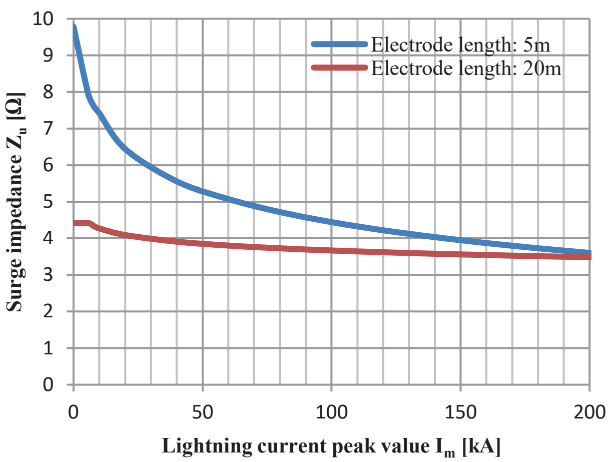

Fig. 7. Grounding surge impedance for different values of the lightning current peak value for identical grounding electrodes placed in soils characterized by different resistivities equal to 40 Ωm and 200 Ωm

Analysis of simulation calculations lead to the conclusion that, for higher grounding electrode lengths, surge impedance and the surge impedance coefficient rise. For grounding electrodes, the parameter called effective length is incredibly important. Extension of the aforementioned value does not improve the quality of lightning current transmission. Grounding electrodes with a length exceeded the effective length are characterized by a disadvantageous increase of surge impedance [9].

Change of the lightning current peak value within the range from 4 kA to 200 kA for 5 m long horizontal grounding electrode, is equal to 0.212. This feature is another argument in favour of using, if possible, a clustered grounding system. In the case of grounding electrodes located in soils with resistivity (greater than approximately 1000 Ωm), surge current reflection phenomena may be observed, which may lead to the need to consider the grounding electrode as a transmission line.

Results obtained on the basis of simulation calculations allow for the estimation of the value of the surge impedance coefficient, which is dependent on the geometrical dimensions of the grounding electrode and the properties of the soil where it is placed. These results also make it possible to assess the impact of the lightning current peak value on the surge impedance of the grounding structure. The simulation model should represent real grounding qualities. The results of simulations and formulas developed by L. Grcev require verification by experimental data from [6].

The comparison of surge impedance coefficient is obtained as numerical calculations in PSpice software or results of L. Grcev's method referenced to the experimental data published by K.S. Stiefanow. This is the basis, making it possible to identify the suitability of a computer simulation and analytical equations for actual measurements. Experimental results are presented in Table 2.

Table 2
Results of Stiefanow's experiments for horizontal grounding electrode rods with radii ranging from 10 mm to 20 mm [6]

Soil resistivity ρ [Ωm]	Electrode length l [m]	Lightning current peak value I_m [kA]		
		10	20	40
		Surge impedance coefficient A [–]		
100	5	0.75	0.65	0.50
	20	1.15	1.05	0.95
200	5	0.55	0.45	0.30
	20	1.00	0.90	0.80

Computer simulation requires some specific parameters for the implemented grounding model. Unfortunately, not all necessary data was included in K.S. Stiefanow's publication [6]. The missing parameters are the intensity of the electric field indicating the presence of discharges in the soil, grounding electrode rod radius, relative dielectric permittivity of soil, and depth of electrode placement. This situation necessitates a few assumptions. All the needed parameters were set according to available data in other publications [11, 13, 24]. In this case, the following were assumed: intensity of electric field initiating discharges in the soil $E_k = 300$ kV/m, depth of the grounding electrode's placement $H = 1$ m, relative dielectric permittivity of the soil $\varepsilon_r = 8$, and radius of the electrode's cross-section $r_0 = 10$ mm. Surge current shape parameters for the simulation were equal to $T_1 = 4$ µs and $T_2 = 10$ µs.

Analysis of grounding electrodes' qualities by computer simulations and the methodology presented by L. Grcev requires determination of the approximation error related to the results obtained in the experiments by K.S. Stiefanow. The approximation error $\delta A_{\%}$ is determined by the following formula:

$$\delta A_{\%} = \frac{\left|A_{\text{measured}} - A_{\text{sym/Grcev}}\right|}{A_{\text{measured}}} \cdot 100\%\,, \tag{35}$$

where A_{measured} is the surge impedance coefficient obtained by K.S. Stiefanow and presented in [6], $A_{\text{sym/Grcev}}$ is the surge impedance coefficient calculated according to the results of the computer simulations or by L. Grcev's analytical method. The approximation error for the surge impedance coefficient is presented in Figs. 8 and 9.

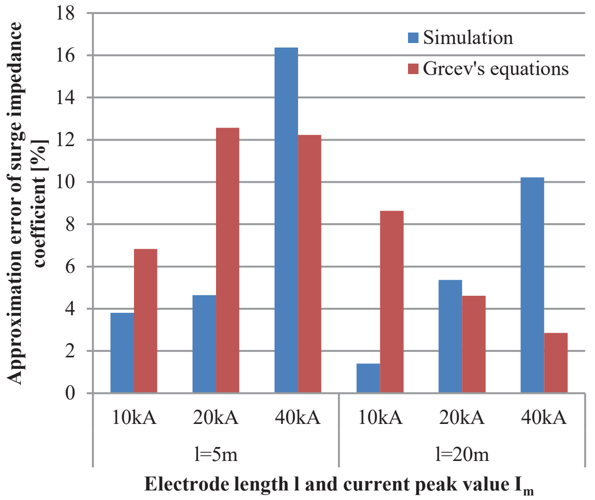

Fig. 8. Approximation error of surge impedance coefficient calculated for soil resistivity $\rho = 100$ Ωm

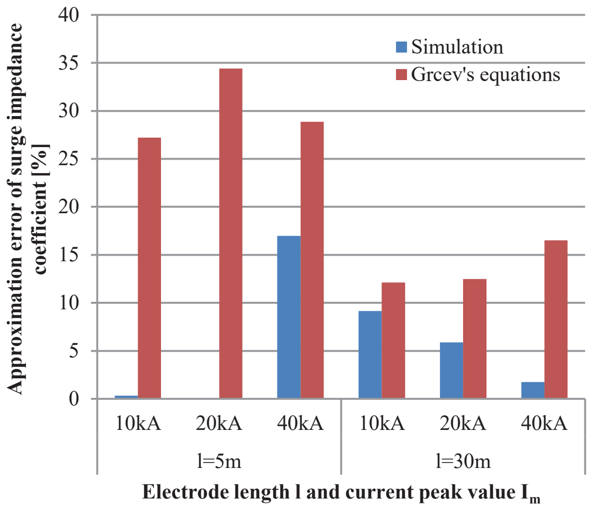

Fig. 9. Approximation error of surge impedance coefficient calculated for soil resistivity $\rho = 500$ Ωm

Analysis of Figs. 8 and 9 leads to the conclusion that simulation allows for obtaining much more representative results than Grcev's analytical method. For most of the considered cases, the approximation error calculated on the basis of the simulation does not exceed 10%. The advantage of simulation is especially observed for grounding electrodes placed in soil with substantial resistivity values.

6. Conclusions

Conducted calculations lead to the conclusion that an increase of soil resistivity also raises the value of grounding surge impedance and the grounding surge impedance coefficient. For grounding electrodes placed in soils with identical properties, length is the most important parameter. In the case of concentrated grounding electrodes, the grounding surge impedance coefficient values are lower than for the extensive ones. This is a consequence of the parameter called effective length, and when it is exceeded, the properties of lighting current transmission are not noticeably improved.

Analysis of simulation results and Grcev's analytic method allows for consideration of which solution gives a better description of grounding qualities. Better results are obtainable from the simulation model. This property is especially observed for higher values of soil resistivity. Grcev's equations may be useful for pre-calculations or pre-evaluation of grounding electrode structures. The methodology presented in [7] has utilitarian potential and requires further experiments, which will lead to improvements in mathematical formulas.

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