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ANALYSIS OF A SIMPLE GROUNDING SYSTEM INSTALLED IN A MULTILAYER SOIL

The aim of the paper is to analyze the influence of selected geoelectrical models on the correctness of a simple grounding system performance estimation. A comparison of different multilayer soil models used to compute grounding system resistance was made as an alternative to typical uniform and two-layer soil conceptions. Experimental tests of a simple grounding system are described. Preliminary measurements were conducted at the new open-air laboratory belonging to Rzeszow University of Technology (RUT), Poland. Finally, measurements of soil resistivity with the use of different methods and at the same time, the ground resistance measurements of simple grounding system were performed. Using the experimental data, a different multilayer soil models were proposed and the grounding resistances of the same grounding system were computed. In case of impact excitations characteristic for lightning currents, the potential distributions around the analyzed grounding system are shown for the selected multilayer soil, and then, the obtained simulation results were compared with the case of the corresponding uniform soil.

1. Introduction

Proper measurement and interpretation of soil characteristics are important for the designing and monitoring of grounding systems, usually done for overvoltage protection purposes. In accordance with [1], the total resistance and potential distribution estimation is necessary to determine hazardous step and touch voltages and potential at different points of installation. It is indispensable to find equivalent geoelectrical representation of soil in any computer simulation. Resistivity measurement is a primary task in determination of geoelectrical models. The parameter is strongly dependent on many factors as changeable weather conditions (temperature, moisture, season), soil type and measurement method. Because of that, it is important to approach each data set individually and take possible impacts into consideration [2]. At present, grounding system studies are based on uniform or two-layer soil models. Precise analyses of complex lightning protection systems (LPS) require more accurate estimation of grounding resistance for low and high frequency components of the lightning current waveform. In the paper different multilayer soil models are investigated and compared considering the grounding system resistance. Measurements of grounding system resistances were conducted at the new test site of lightning protection belonging to Rzeszow University of Technology (RUT), Poland [3]. The open test site was built basing on experience obtained during cooperation with the lightning research group from University of Florida, Gainesville [4]. The area was divided in two parts (Fig. 1). The more complex part is equipped with a transformer station, a power line and a test house model. The house model is connected with the transformer by an underground cable. Intentionally it was designed to conduct research of current distribution in LPS of a typical real scale building and interaction with power system, mainly for usage of overvoltage protection [4]. The results of already done measurements and analysis have shown new technical capabilities in lightning current distribution studies.

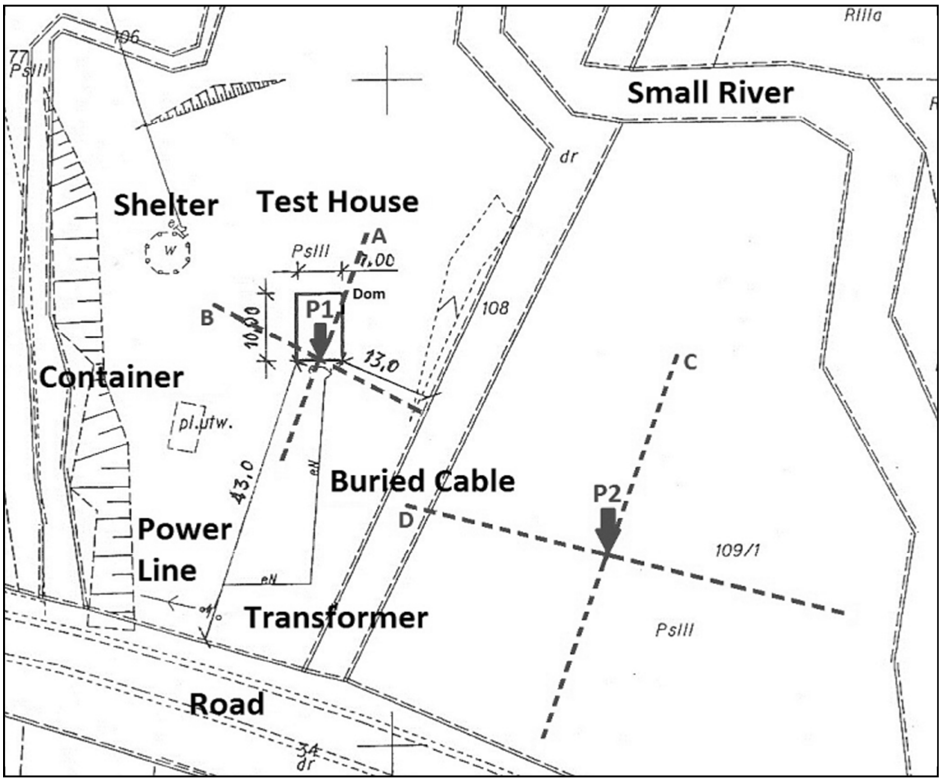

Fig. 1. Top view of the test site of RUT with indicated soil resistivity and grounding resistance measurement profiles (dashed lines)

Another application of the test site is investigation of the nature and physics of typical grounding systems. The terrain with profiles C and D is situated in non-urbanized area (Fig. 1). Neither buried metallic structures nor power system facilities exist there. Preliminary measurements showed no influence of nearby groundings. The experimental data were compared to simulation results regarding resistance and potential distribution around the grounding system in one of typical configurations used practically. Note that the size of the above mentioned zone is about 45 m in the diameter, so the currents flowing around Point P2 (Fig. 1) were not disturbed. More detailed information on the configuration and features of the facilities at the test site in Huta Poreby can be found in [5].

2. Measurement setup

Presently, resistivity characteristics of typical soils are well known. Unfortunately, there is lack of data obtained with application of several measurement methods simultaneously (Fig. 2). Therefore, different variations of the four-electrode method of measuring soil resistivity were examined. The method is based on the voltage and current ratio obtained from measurements with probes buried in the ground at specific spacings. In case of Wenner method, as the most practical approach, the spacings between probes are the same. Schlumberger proposed an arrangement where distances of adjacent current and voltage probes are equal. This modification is useful when sensitivity for large probe-spacing should be increased. This method was applied to penetrate soil volumes at different depths for several particular current probe spacings. Moreover, further generalization of the method was done as shown in Fig. 2. It should be emphasized that each data set consists of several individual measurements obtained for different probe spacings along both lines C and D (Fig. 1). The measurement results were used for computer simulation.

The above-mentioned resistivity measurement methods were described more precisely in [6]. Moreover, some practical problems of Wenner and Schlumberger methods were presented including error minimization techniques.

In case of grounding system resistance estimation the fall-of-potential method was applied. An arrangement of experimental setup is presented in Fig. 3. Resistance measurements were conducted for several grounding rod depths varied from 0.1 m to 1.5 m. Also potential characteristics were collected indirectly for this configuration. The potential was measured at the ground surface by changing the position of the inner probe from 0.1 m to almost 40 m. During this measurement the grounding rod depth was 1.5 m. Additionally, the potential measurement was done in four perpendicular directions but no differences were observed.

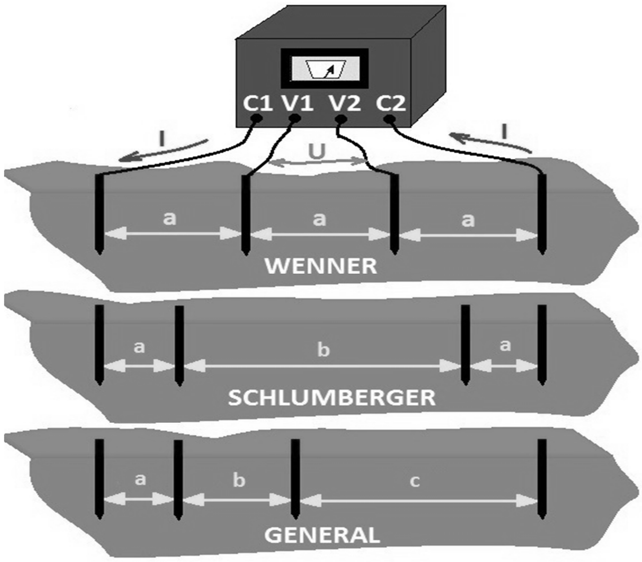

Fig. 2. Resistivity measurement methods used in order to obtain various soil characteristics

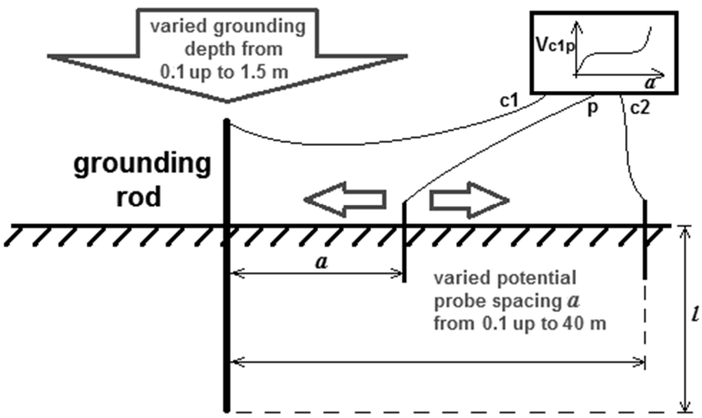

Fig. 3. Grounding resistance and potential measurement procedure. Note that grounding depth *l* as well as potential probe spacing *a* were varied

3. Geoelectrical soil model selection

A comparison of different multilayer soil models with a typical uniform and horizontal two-layer approach was the general purpose of the entire simulation.

Computer analysis was conducted in CDEGS. The packet is a powerful set of integrated engineering software tools designed to analyze accurately the problems involving grounding, electromagnetic fields and cathodic protection. Three CDEGS interfaces were used: RESAP, MALZ and HIFREQ [7]. RESAP module was applied to the interpretation of measured soil resistivity data and determination of equivalent ground structure models. In [8] the module and its computation algorithms were presented in detail also for the multilayer approach. As an alternative to RESAP, Matlab program dedicated to geoelectrical ground model estimation was prepared. At present, the interface is able to determine structure consisting of horizontal layers of non-limited thickness and resistivity factor. The layers are grouped in volumes called zones. The number of layers in each zone and the zone depth should be defined by the user. These features give good opportunity to adjust the density of layers to the particular grounding system configuration. The already obtained results show that the multilayer conception can be more accurate than uniform or two-layer models in grounding system resistance estimation [5, 9].

Considering ground resistivity measurement, corresponding data sets obtained for profiles C and D differ insignificantly. Therefore, the results were averaged, which implies no horizontal resistivity variation. In order to obtain more credible geoelectrical models, especially for the upper soil layers, the Wenner method, the Schlumberger method and the General method data was combined. Consequently, in case of the Schlumberger-based simulation also the Wenner measurement was taken into account. The general method-based models were computed with the application of all data sets as input. The simulation proceeded without any external restrictions. Both resistivity as well as layer thickness were determined by CDEGS module completely. The results relative to the uniform and horizontal two-layer conception are presented in Fig. 4, and various multilayer models were compared in Fig. 5. Matlab simulations of twenty-layer soil structures were also included in the same axis.

The simulation results show that on the basis of the same input data different geoelectrical models can be computed independently. The models obtained from CDEGS with the application of the Wenner, Schlumberger and General theoretical rules are varied regarding both resistivity and layers thickness. It can be easily seen from Figs. 4 and 5 that there is no simple relation between inter-electrode spacing (average spacing between current and potential probes) and computed resistivity profiles. Especially, in case of General two-layer model the curve shape and the measurement data vary considerably. The uniform and two-layer horizontal models are not diversified as much as the multilayer models. The results from the Schlumberger and General method are very close. Considering the two-layer models, the main difference is the top layer thickness, which is greater in case of the Wenner method and less for General method. It should be emphasized that the resistivity of the top layer is about six times

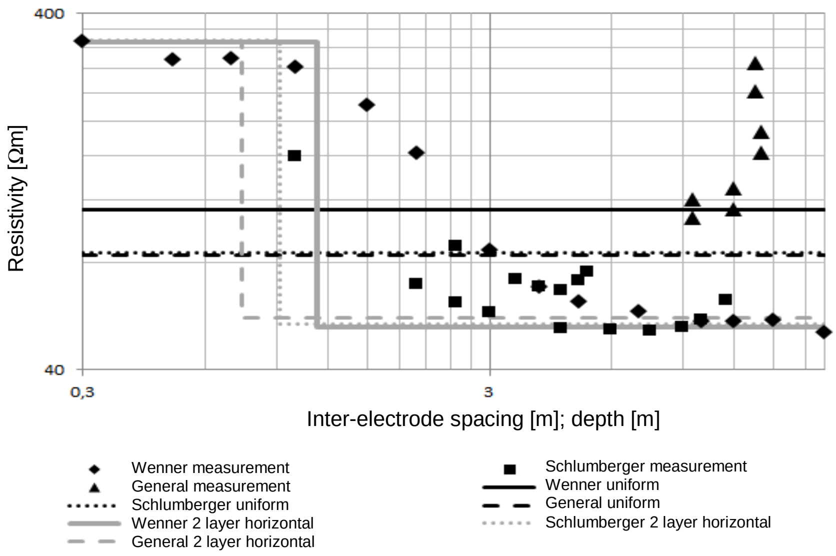

Fig. 4. Typical uniform and horizontal two-layer geoelectrical soil models obtained from CDEGS. Notice logarithmic scale of both axes

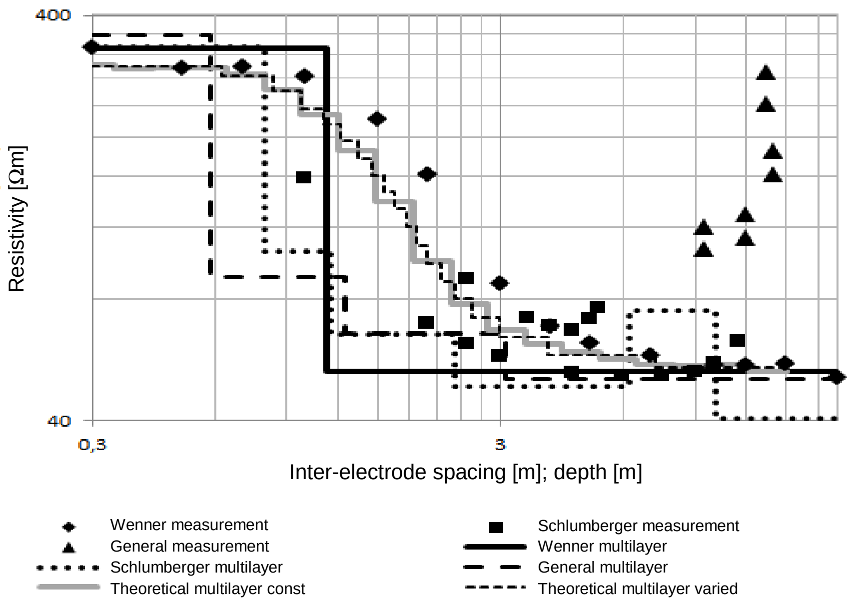

Fig. 5. Comparison of multilayer geoelectrical soil models done using RESAP and dedicated Matlab program. Horizontal axis: inter-electrode spacing for measurement data, depth for geoelectrical models

greater than the bottom one. The disproportion may have influence on grounding system resistance reduction. An interesting result was obtained from the comparison of models based on the Wenner method of computation (Figs. 4 and 5). Despite the technical capability of maximum twenty-layer fit only two-layer model was proposed. Moreover, the error, defined by CDEGS as the maximum acceptable root mean square between the measured data and the corresponding values generated from the computed soil model [7], was about 4.5%. It means that this was decidedly the most accurate simulation. More complex geoelectrical structures were obtained using the Schlumberger and the General data. Some similarities are observed between the models. In each case the order of resistivity is comparable, for Schlumberger deep conductance variations are present. Theoretical multilayer curves were computed with the application of Matlab. Two cases are considered in respect of logarithmic depth scale: equal and varied layer thickness. The next assumption was the Wenner coefficient k = 0.75 which means that the resistivity computed for particular electrode spacing a is present at the depth of ka = 0.75a [10]. The models were both exported to CDEGS as twenty-layer and used for the grounding system performance simulation.

4. Grounding system resistance and potential distribution analysis

Further simulation was conducted in another CDEGS module, MALZ. The obtained geoelectrical models were imported to the module. Typically MALZ is used to analyze and design grounding systems for HVAC and HVDC power stations, substations, transmission line towers or to design anode beds for cathodic protection installations up to 3 MHz. Grounding system resistance was computed for all geoelectrical models individually and then compared with measurements (Fig. 6). In order to obtain grounding resistance special procedure was used. The fall-of-potential method was implemented as shown in Fig. 3. The resulting measurement curve was identified as resistance between the grounding and a specified point at the ground surface. For distances between 20 and 25 m resistance become constant and the value is defined as grounding resistance. The curve can be directly rescaled by the current to potential relationship with the application of Ohm’s law. A similar operation was performed in theoretical simulation done in MALZ where the measurement setup configuration of the fall-of-potential method was implemented. The outer electrodes were simulated as 1 A current source at 128 Hz. The potential probes were defined by profile points where potential should be computed. This current value was selected to get the simplest scaling factor between potential and resistance. Grounding system resistance based on typical uniform and two-layer models are strongly underestimated. The use of simple models can cause serious problems during a grounding system design process. Moreover, overvoltage protection levels could not be determined properly. More complex twenty-layer models fit better but still some discrepancy is observed, especially near the ground surface. In Figure 6 two additional models are shown: the uniform structure with the resistivity of 195 Ωm and twenty-layer soil with the Wenner coefficient of k = 0.63. The total resistance computed with the application of the models was equal to the measured one.

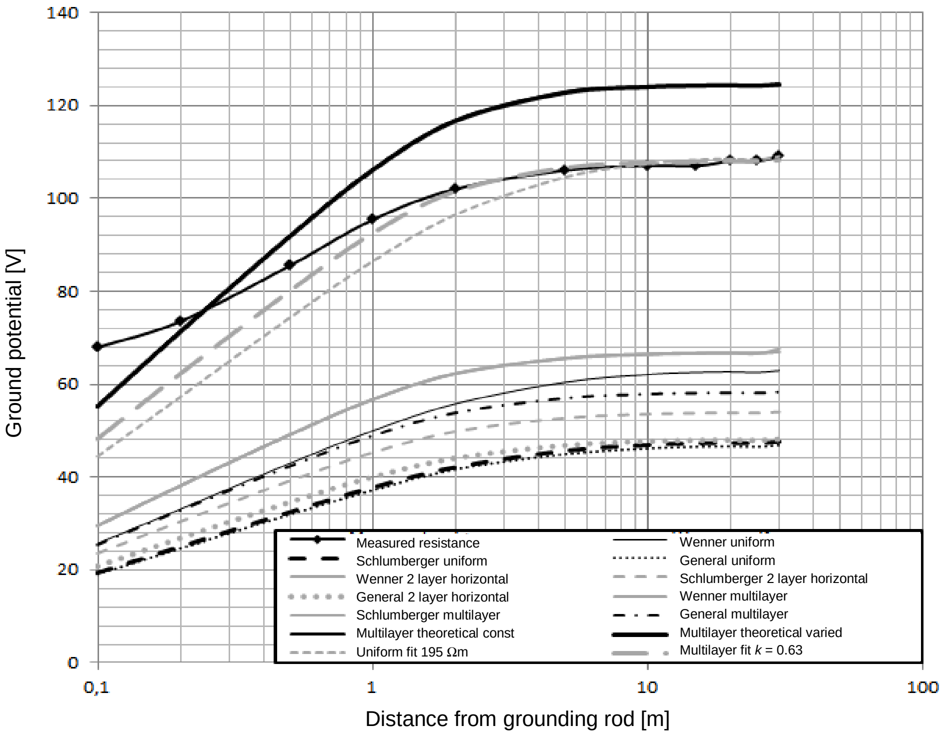

Fig. 6. Potential distribution at the ground surface in low-frequency range. Ground potential is considered under assumption of zero potential of the grounding system. Therefore, potential values at distance of 25 m can be considered directly as grounding resistance

The following simulation was based on the same measurement setup as the one above-mentioned but the length of buried grounding rod was changing (Fig. 3). The measurement results were presented in Fig. 7. Due to better conductance of the bottom layer the grounding resistance decreases with depth. Generally multilayer models are closer to the real function than the uniform soil ones, especially when the grounding system length is relatively short. Some differences are observed at the depths corresponding to the boundaries of layers. When the rod reached the soil volume of better conductance then grounding resistance decreased immediately. It is clearly visible for two layer models with extremely high resistivity difference.

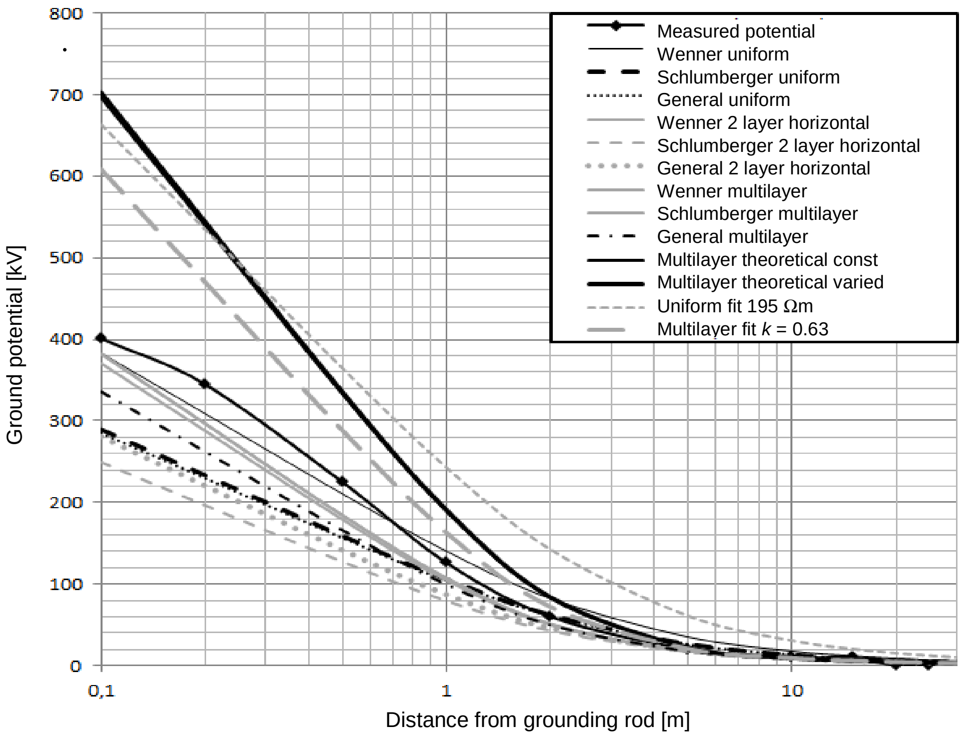

Fig. 7. Influence of varied multilayer soil models on the change of grounding system resistance with depth

Finally, the proposed models were tested for lightning current distribution using the HIFREQ. Typical current waveform defined in the CDEGS was injected to the grounding system. The potential distribution was analyzed at the time point of 5 μs after stroke origin when the maximum value is reached (Fig. 8). Additionally, the measured potential scaled up linearly by 10 kA low-frequency current was presented. The conducted simulations show that the dependence of grounding system resistance on the frequency is less than 1% for the bandwidth up to several megahertz. The potential function is different for various geoelectrical models. For this particular instance, in contrast to the low-frequency range, the simple soil structures as the Wenner uniform or the two-layer are most accurate. The simulation results are comparable with the measurements. Despite the conformity with grounding resistance (Fig. 6), the fitted uniform 195 **Ω**m and the multilayer k = 0.63 models give considerably overestimated results. The values at the ground surface close to the buried rod are almost two times greater than the corresponding result for low-frequency. Theoretical multilayer structures also give overestimated values. The reason is the relatively high resistivity of several simulated top layers increasing soil resistance just above the grounding system.

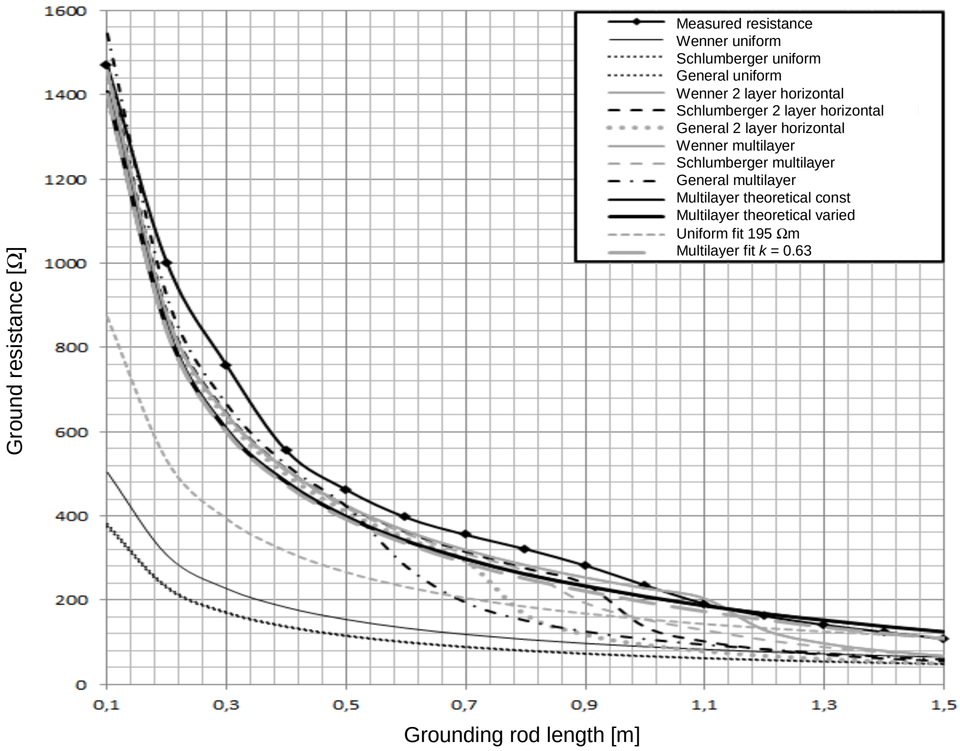

Fig. 8. Potential distribution at the ground surface for 5/20 µs 10 kA lightning current surge injected directly to the grounding system

5. Conclusions

The research done at the test site provided opportunity for comparison of the simulation results with the measurements. The performed simulation allowed to check the influence of different geoelectrical models on the resistance and potential distribution of typical grounding system. Considering lightning conditions, the uniform, the two-layer and the multilayer approach were used for grounding system resistance estimation and potential distribution computation. Under certain conditions, the two-layer horizontal model is a reasonable compromise between precision and simplicity of soil structure. The results for both slow- and fast-current sources show significant influence of the assumed geoelectrical model on performance of the entire grounding system.

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ANALIZA PROSTEGO UKŁADU UZIEMIENIA POGRĄŻONEGO W GLEBIE WIELOWARSTWOWEJ

S t r e s z c z e n i e

Celem artykułu jest analiza wpływu wybranych modeli geoelektrycznych gruntu na poprawność symulacji prostego układu uziemienia. Szczegółowej analizie poddano typowe modele jednorodne oraz dwuwarstwowe, a następnie porównano je ze znacznie bardziej złożonymi koncepcjami gruntu wielowarstwowego. Uzyskane rezultaty odniesiono do wyników eksperymentalnych. Pomiary wykonano na poligonie badawczym w Hucie Poręby należącym do Politechniki Rzeszowskiej. Rezystywność gruntu na terenie poligonu uzyskano trzema metodami: Wennera, Schlumbergera oraz ogólną czteroelektrodową. Jednocześnie zmierzono rezystancję oraz rozkład potencjału wokół badanego układu uziemiającego. Na podstawie zebranych wyników zaproponowano kilka modeli geoelektrycznych gruntu, dla których odpowiednio wyznaczono rezystancje uziemienia. Dokonano również analizy obejmującej rozkład potencjału generowanego rozpływem prądu udarowego typowego dla wyładowań piorunowych. Uzyskane rezultaty porównano z wynikami dla gruntu jednorodnego.

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