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Reduction of the step voltages of MV/LV substation grounding system based on shaping electric field

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Abstract: The article presents the analysis results of the effectiveness limitation of the step voltage by forming an electric field on the ground surface. For shaping the electric field, a method consisting of screens placed around the point of the earth current flow was used. The analysis was performed using an example of an MV/LV substation grounding system. This research was conducted applying a mathematical model of the grounding system and screens by means of the finite element method. The influence of metal, insulating screens and surface material on the step/touch voltage values for the considered grounding system was estimated. Most of the methods described can be applied in practice. In the opinion of the authors, the method of using screens made of insulating and conductive materials has not been sufficiently described in the literature. Moreover, in the available literature there is no in-depth analysis of the described electric field shaping methods.

Key words: grounding system, step voltage, touch voltage, IEEE 80-2013 standard

1. Introduction

One of the elements of the power system responsible for its proper operating and safety of use are grounding systems. The basic part of such installations is the earth electrode located below the ground level. For the simplest structural solutions, it is implemented in the form of a metal strip buried horizontally, vertical rods or both. The metal strip is placed underground parallel to the ground surface. When there is a need for a grounding system with low resistance R_E for power substations, it is made in the form of a grid made of steel tape or rods with dimensions depending on the planned or existing power substation. The basic grounding system parameter, which is the resistance of the grounding system electrode, depends on such factors as the geometrical dimensions of the buried grid and the soil resistivity ρ. Local factors such as the chemical composition of soil, its temperature or humidity result in large ranges in the resistivity values.

The second parameter characterizing the grounding system is the value of the step voltage V_{step}. This value is defined as the difference of potentials on the ground surface between points spaced from each other by the size of the contractual step (1 m). From the point of view of designing the grounding installation, the step voltage cannot exceed the set limit value in order to eliminate the possibility of the electric shock of a person standing on the ground surface.

The next characteristic parameter describing the degree of electric shock risk is the touch voltage V_{touch}, which is measured as a potential difference between the conductive part of the grounding system accessible to touch and a point on the ground surface at 1m from it. Figure 1 depicts the step voltage V_{step} and the touch voltage V_{touch}.

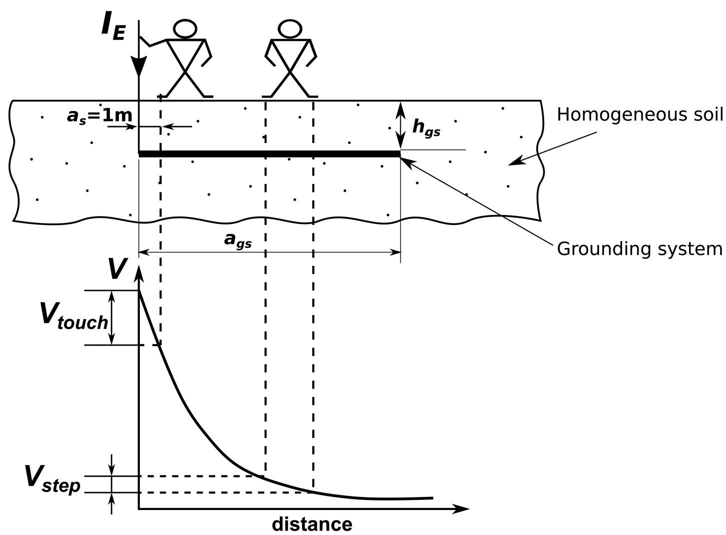


Fig. 1. Definition of step voltage V_{step} and touch voltage V_{touch}

The method of measuring the step/touch voltage is described in [1]. Another method of estimating the step/touch voltage is calculating the distribution of the electrical potential on the ground and its resistance. The value of the step/touch voltage cannot exceed the recommendations contained in the standards [2, 3]. The essence of the problem is to find a solution to the flow field equation in a conductive environment around an electrode buried in the ground. For stationary fields, this is the solution of the Laplace Equation (1) for the electric potential of V_E.

$$\nabla^2 V_E = 0. \tag{1}$$

The accurate solution of Equation (1) can be obtained using analytical methods for simple theoretical cases and assuming the uniformity of soil parameters. In the case of complex grounding system geometry, other methods of solving Equation (1) are used. Analytical methods used to design a grounding system are an issue raised in the subject standards [2–4]. Due to the difficulty in determining the boundary conditions, with the complex shapes of the search areas of the electric field, analytical methods are used for theoretical cases such as the hemisphere or roller. The solutions obtained for such geometry make it possible to verify the results obtained by numerical methods of calculation and estimation errors. In numerical methods, the shape of the considered area is virtually arbitrary, and the only limit is computational effort.

When initiating a grounding system project, one should first take the following input data into account: the soil resistivity ρ (Ωm), earth current I_E (A), earth current flow time t_C (s), geometric dimensions of the area to be occupied by the grounding system, the depth of burying the grounding system h_{GS} (m), the material used for its construction, the type and thickness of the surface material.

The most reliable method of evaluating the resistivity of soil is to perform measurements on the grounding system location. In the absence of such possibilities, the tables contained in the standards can be used [2–4]. The value of the current I_E and the duration of its flow t_C depend on the structure of the power network and the adopted protection system settings. The burial depth of the earth electrode h_{GS} is usually between 0.5 and 1 m. The permissible values of voltage are derived from the assumed time of the earth current flow and they are given in a graphical or analytical form in [2–4].

Paper [5] promotes the awareness of hazards connected with the potential on the surface of the ground. It has been proven that the earth potential values may be above the permissible value if the voltage is up to 220 V AC. Paper [6] presents the method of measuring the existing grounding systems and provides the results and statistical data for 6 selected substations that have been recently designed. To calculate the ground resistance quickly and conveniently with the required accuracy, paper [7] proposes an algorithm that uses the method of fitting the least squares curve and hyperbolic matching functions to match the resistivity and soil resistance of the layered soil model. Article [8] presents research on the impact of various soil types and shock wave characteristics in the aspect of human safety. The test focuses on the step/touch voltage and transferred potentials generated by lightning striking the grounding system and the potential electrical shock hazard for humans. The problem of finding the potential in the amorphous soil is discussed in [9], where an analytical method has been proposed. This method is used to study the electrical properties of a ground electrode connected to a metal mesh which is embedded in concrete. Article [10] contains the development of a new methodology for measuring earthing resistance and the step voltage in the supply network of urban power substations. The article includes the mathematical model for estimating and predicting the work of the earth electrode, based on the polynomial regression from the database method (PRED).

A grounding system modelling is a multi-stage and relatively complicated process. In the literature [11–16], a number of mathematical models and computational methods are described. In the first modelling stage, the input parameters such as the geometry of the earth electrode, the physical and chemical properties of the soil and the number of earth current flow points should be selected. In the next stage, a mathematical model is formulated, the form of which depends on the chosen solution (analytic or numerical). The mathematical model is then implemented in a given programming environment if a numerical method is used for the solution. In the fourth stage calculations are made. The calculation time is closely related to the numerical method used. In the last stage, the obtained results of calculations should be validated. The choice of the input parameters of the model should be made very carefully because the adoption of imprecise or incorrect values results in obtaining erroneous results. The most difficult aspect related to the selection of input parameters of the grounding system model is the determination of the right soil parameters. This issue is discussed, among others, in [17]. The typical values of the basic soil parameter, which is its specific resistivity, are included in many subject standards and manuals e.g. [2–4, 18]. The problem of choosing the right value of soil resistivity is closely related to the problem of whether the soil can be treated as an area with homogeneous properties or whether it is a heterogeneous area. This is described in the literature in [12–14]. In the article [12], the authors discuss in detail the equivalence of the use of a significantly simplified homogeneous or two-layer soil model with a multi-layered model. In [12], an analysis and comparison of the grounding resistance and the touch voltage was made for various equivalent soil models. A solution to the issue of ensuring that a one or two-layer model is representative of a multi-layered structure is presented. An attempt was made to answer the question whether one can develop a good soil model that allows to properly determine various parameters defining the grounding system as resistance, touch voltage and current distribution simultaneously. The authors of the article [12] state that it is difficult to find a single-layer model that could successfully replace a complex multi-layered model. The selected one-layer model compared to the multi-layered one gives similar results for the resistance of the earth electrode, but the obtained values of the touch voltage are divergent. Paper [19] presents a numerical technique on the basis of the Boundary Element Method (BEM) for the analysis of horizontal and vertical grounding systems. The proposed method has been demonstrated by its application to the actual grounding network, taking into account different types of soil models. Realizing the needs of engineers for a flexible and reliable tool for estimating and predicting the behaviour of a grounding system, paper [20] has developed a model that accurately describes and predicts the variability of soil resistance. The main purpose of [21] is to develop an optimization model for designing grounding systems for electrical substations. The design of the grounding grid in the substation is formulated as a linear integer programming problem. The developed optimization model takes into account structural features, in addition to technical and safety requirements related to the construction, installation and operation of these power networks. Typical grounding systems configurations are used in MV/LV distribution substations often without assessing their performance in terms of safety in the event of a critical electric shock due to step/touch voltages which arise in the event of a ground fault. Thanks to this, the safety of an existing or new MV/LV substation can be easily assessed using a safety curve. In [22] the simple safety assessment method of typical MV/LV substation groundings is introduced on the basis of simple calculations.

In practical applications, different models should be used to calculate resistance and touch voltage. A grounding grid can be replaced with a substitute diagram with fixed constants, which is presented in [23]. The model consists of resistances representing individual grid segments and current sources. To determine the flow of current in the circuit constructed in this way, the node potential method is used. Paper [24] presents an advanced method for calculating grounding systems based on the calculation of a substitute diagram of the buried electrodes forming one unit. In the case of designing the grounding system for lightning protection, analysis of its operation in the transient states can be used [15].

This paper proposes the use of screens made of conductive and non-conductive materials to properly shape the electric field on the ground level. Thanks to this, lower values of step voltages can be obtained, which significantly improves the effectiveness of shock protection. Analytical methods known from the literature [2, 3] used in the design of earth electrodes make it possible to include, as a technical measure only, the surface material. If screens are used to shape the electric field, it is virtually impossible to obtain a solution using analytical methods. To analyse this problem, a model of a grounding grid with assumed parameters was made. To determine the distribution of the electric field around the working earth electrode, the numerical method called Finite Element Method (FEM) was used. This method is used to calculate the distribution of electromagnetic field in the analysis of various engineering problems [25, 26]. The calculations of the electric field distribution were made in the steady state. Both step and touch voltages were analysed in the paper.

Most of the methods described can be applied in practice. In the opinion of the authors, the method of using screens made of insulating and conductive materials has not been sufficiently described in the literature. Moreover, in the available literature there is no comparison of the effectiveness of the described electric field shaping methods.

2. Limiting the value of the step/touch voltage by forming an electric field on the ground surface using conductive and insulating screens

Ground grids are the integral elements of power substations. Their proper design, realization and maintenance reduce the risk of electric shock to the station's staff and even to an ordinary person. Such a risk exists with MV/LV stations as they are most numerous and often accessible to ordinary people. Therefore, the analysis of the effectiveness of using screens to limit the values of step/touch voltages was performed for the MV/LV substation grounding system.

The considered grounding system is made in the form of a grounding grid made around the substation. Due to the design constraints, the current flow point is located on the outer edge of the grid. This positioning of the current flow point is least favourable due to the occurrence of a large gradient of the electric field potential. The value of the earth current results from the assumption of a ground fault on the MV side. In this case, a part of this current closes via the grounding system of the substation.

The change in the way the neutral point works in the power system from isolated to grounded causes a significant increase in the value of the earth current (from several dozen to even three hundred amperes). The existing MV/LV grounding grid was not designed for such a significant increase in the value. There is therefore a supposition that the permissible values of the step and touch voltages defined in [4] will be exceeded. Obtaining the required values of touch and step voltages requires a modification of the grounding grid. The occurrence of hazardous shock voltages can be effectively limited by reducing the resistance to earth R_E. This can be achieved, for example, by increasing the size of the grounding grid or its modification. In practice, the modernization consists in making additional vertical electrodes connected to the existing grid, and then performing a series of necessary measurements, which is not technically possible in every case and usually involves a lot of investment. Another method of reducing the step voltages is to shape the electric field on the ground surface. Proper shaping of the electric field makes it possible to obtain the smallest step voltage values [2–4]. As mentioned above, surface material is applied on the ground surface. The application of screens in the most hazardous areas is an alternative to using the surface material. The applied surface material can be made of materials with higher or lower specific resistivity than the native soil, which causes a change in the permissible step voltage [2,3]. The technical method in the form of screens does not change the permissible value of shock voltages.

For the analysis, the authors assumed the dimensions of MV/LV grounding grids, soil resistivity and the grounding current value. To analyse the effect of screens on the shaping of the electric field, a simple grid with dimensions 6.3 × 6.3 m, buried at the depth of $h_{GS} = 0.8$ m was used during the work of the earth electrode. The grid was made of steel with mesh number $n = 4$. The model of the grounding system is shown in Figure 2. The flow point is located on the edge of the grid. For the calculations, it has been assumed that the ground has specific resistivity $\rho = 100$ Ωm. For the analysis a system with isolated neutral was chosen. The value of the earth current is computed as:

$$I_E = r \cdot I_C\,, \tag{2}$$

$$I_C = \sqrt{3} \cdot \omega C_C \cdot V_R\,. \tag{3}$$

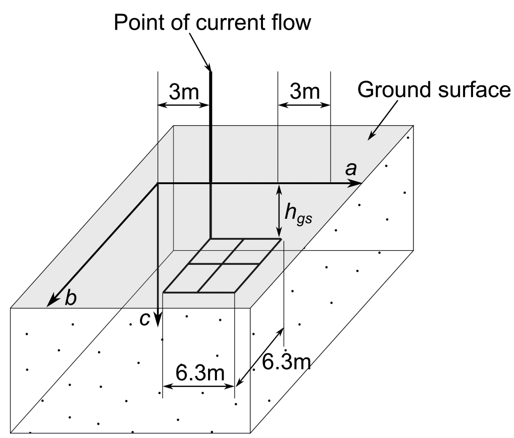


Fig. 2. Ground grid layout (soil 60 × 60 × 30 m)

According to [4] for single-core XLPE cables (10 kV and 20 kV) with copper screen $r = 0.5–0.6$. For calculations $r = 0.6$, $\omega C_C = 7.70$ mS and $V_R = 15$ kV were assumed. Thus, the earth current equals 40 A.

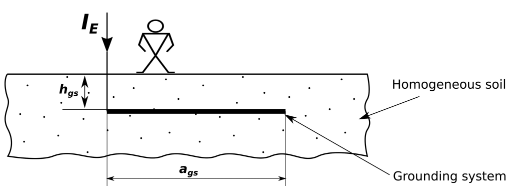
For easy presentation of the results obtained, an auxiliary coordinate system was used (the coordinate axes are marked as a, b and c). The coordinate system is located on the ground surface, and its beginning is 3 m from the point of the current flow. The results presented further in Figures 5 to 7 are shown for axis a, which was introduced in the place of the expected maximum value of the electric potential on the ground level V_E (step voltage V_{step} or touch voltage V_{touch}). For the flow field, the earth current flows into the point of the current flow with values resulting from the previously assumed assumptions. The soil model has the dimensions of 60 × 60 × 30 m. The boundary condition is the acceptance of the reference earth potential on the outer edges of the soil model ($V_E = 0$).

The calculations of the electric field distribution have been made for the following grounding grids variants:

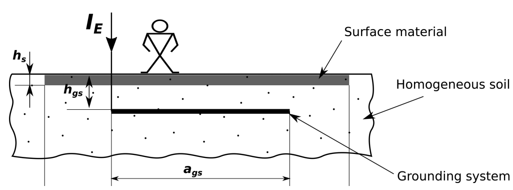
1) the grounding grid in homogeneous soil,
2) the grounding grid with surface material 8.3×8.3 m, $h_s = 3$ cm, $\rho_s = 1$ Ωm,
3) the grounding grid with surface material 8.3×8.3 m, $h_s = 3$ cm, $\rho_s = 2000$ Ωm,
4) the grounding grid with isolation screen 8.3×8.3 m, $h_{sc} = 0.4$ m, $\rho_s = 10e + 12$ Ωm,
5) the grounding grid with isolation screen 3×3 m, $h_{sc} = 0.4$ m, $\rho_s = 10e + 12$ Ωm,
6) the grounding grid with metal screen 3×3 m, $h_{sc} = 0.4$ m.

In the proposed modernization variants through the application of a surface material, the value of the coefficient C_s [2] is 60.4 for $\rho_S = 1$ Ωm and is equal to 0.43 for $\rho_S = 2000$ Ωm. For such assumptions, the grounding grid model made in the three-dimensional space in the ANSYS environment was made using the FEM method. The assumed aim of the simulation calculations is to select such a modernization variant of the grounding grid as to obtain the minimum value of the step voltage without changing its geometry and/or construction.

The cross sections of the grounding grid models for variants 1, 2 and 3 are shown in Figure 3. The cross-section of the grounding grid model for screen variants 4, 5 and 6 is shown in Figure 4.



(a)



(b)

Fig. 3. The cross section of the grounding grid model for variant 1(a); the cross section of the grounding grid model for variants 2 and 3(b)

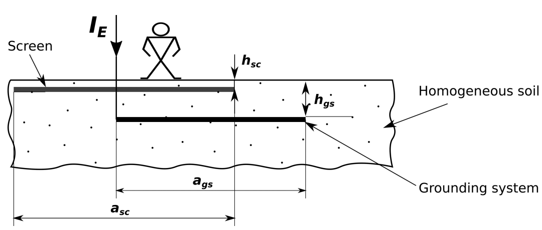


Fig. 4. The cross section of the grounding grid model for variants 4, 5 and 6

The surface material on the ground level is made of a material layer with a given resistivity of proper thickness $h_s = 3$ cm, in the shape of a square with a side wider than the outer edge of the earth electrode by 1 meter. The surface material has been symmetrically arranged over the buried earth electrode. The screens are in the shape of a square buried at half the depth of the earth electrode symmetrically around the current flow point.

3. Analysis of the obtained simulation results

For the above assumptions, calculations of the electric potential distribution V_E were made. The calculation results of the electric potential distribution V_E along the axis a on the ground level for homogeneous soil (variant 1) are shown in Figure 5(a). The highest value of the V_E potential occurs at the point of the earth current flow and it is 240.94 V. The distribution of potential on the ground over the buried earth electrode is fairly even. A large increase in the potential value occurs on the ground along the edges of the earth electrode. After the application of the surface material with resistivity $\rho_s = 1$ Ωm (variant 2), the distribution of the potential has changed, as illustrated in Figure 5(b).

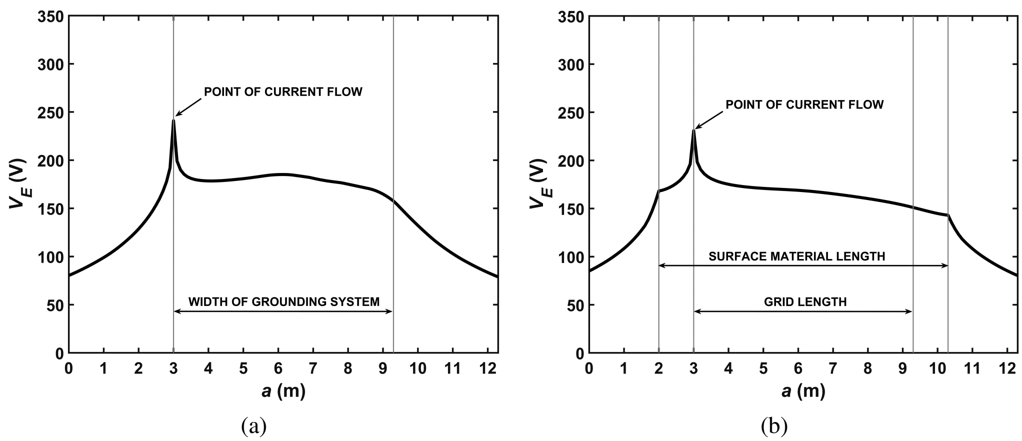
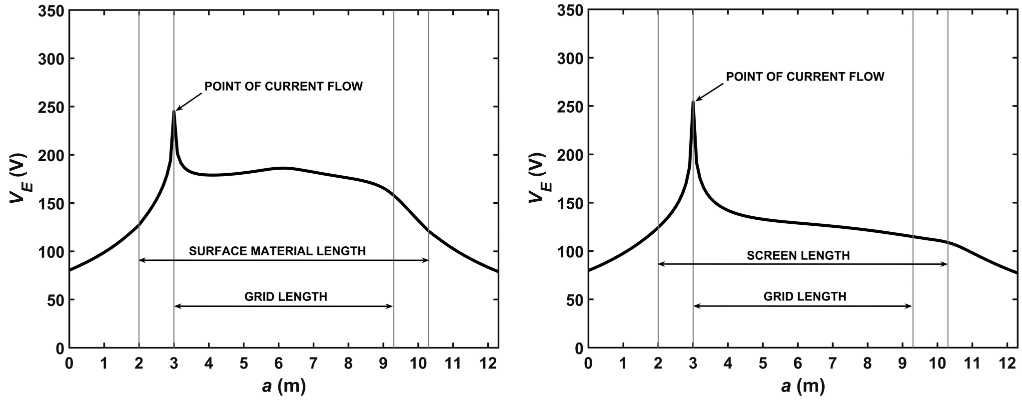


Fig. 5. Distribution of the electric potential V_E along the axis a on the ground level for homogeneous soil (a); distribution of the electric potential V_E along the axis a on the ground level for surface material with $\rho_s = 1$ Ωm (b)

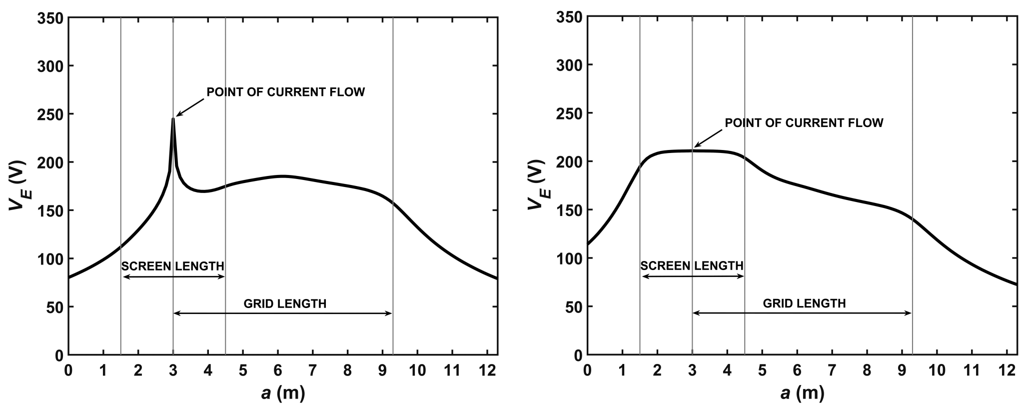
The maximum value of the potential at the point of the current flow decreases slightly. Noticeable changes occur in the area of 2 m from the edge of the earth electrode. Potential values do not decrease as fast as for variant 1. The use of the surface material with resistivity $\rho_s = 2000$ Ωm does not change the distribution of the potential on the ground. It is practically identical to that for homogeneous soil (Figure 6(a)). The application of the surface material, with both low (variant 2) and large (variant 3) resistivity, did not bring the expected results, because the potential of the ground surface around the current outlet point was not reduced. Therefore, calculations were made for the modernization variants in which shields of insulating and metal (steel) materials were used to shape the electric field on the ground level. The calculation results of the electric potential on the ground surface for the insulating screen of dimensions 8.3×8.3 m (variant 4) are shown in Figure 5(b) and for the insulation screen with dimensions 3×3 m (variant 5) in Figure 7(a).

Unfortunately, the use of insulation screens also did not bring the expected effects in the form of the electrical potential at the runoff point and its even distribution. In addition, for variant 4, the highest value of the electric potential was 254.04 V (Table 1). Based on the calculations made for



(a) (b)

Fig. 6. Distribution of the electric potential V_E along the axis a on the ground level for surface material with ρ_s = 2000 Ωm (a); distribution of the electric potential V_E along the axis a on the ground level for isolation screen 8.3 × 8.3 m (b)



(a) (b)

Fig. 7. Distribution of the electric potential V_E along the axis a on the ground level for isolation screen 3 × 3 m (a); distribution of the electric potential V_E along the axis a on the ground level for steel screen 3 × 3 m (b)

variant 6 (Figure 7(b)), in which the steel screen is used, the distribution of the electric potential on the ground surface is more uniform in the vicinity of the current outlet point. The maximum value of the potential is lower than in the previously analysed cases. For the area on the ground level, the value of the electric potential drops markedly with increasing distance from the current outlet point. This phenomenon occurs for all variants of the grounding system modification.

The main aim of the proposed methods for the modification of the grounding system is to strive for a possibly homogeneous distribution of the electric potential on the soil surface.

Table 1. Maximum values of the electric potential V_E, step voltage V_{step} and touch voltage V_{touch} for the analysed variants of modernization

Variant of moderniza-tion	**The maximum value of the electrical potential V_E (V)**	**The maximum value of the step voltage V_{step} (V) (touch voltage V_{touch})**	**The percentage value of the electric potential V_E^{PU} (%)**	**The percentage value of the step voltage V_{step}^{PU} (%)**
1	240.94	112.32	100	100
2	230.86	62.64	95.82	55.77
3	244.78	117.49	101.59	104.60
4	254.04	129.66	105.44	115.44
5	244.58	115.18	101.51	102.55
8	210.80	60.45	87.49	53.82

Consequently, this will provide the desired step voltage V_{step} limitation. The best effects on the shape of the electric field (the distribution of the potential) are obtained for the surface material with resistivity $\rho_s = 1$ Ωm (variant 2) and a steel screen of dimensions 3.3×3.3 m (variant 6). In the case of using the surface material with a resistivity of $\rho_s = 1$ Ωm (variant 2), however, it was not possible to limit the occurrence of a large potential gradient in the immediate vicinity of the current flow point. The step voltage values V_{step} have been determined on the basis of the obtained electric potential distribution. Step voltages were determined in accordance with the definition presented in [2] as the difference in the electrical potential between the points separated by 1 m from each other. The value of the step voltage clearly shows the effectiveness of the electric shock protection. If this value is lower, the protection against electric shock is more effective. The most unfavourable case occurs when a person is standing at a distance of 1 m from the point of current flow and touches the metal conductive elements of the grounding system.

The percentage reduction/increase values of the electrical potential, the step and touch voltage were calculated using (5) and (6) and the results are given in Table 1. The values of the step voltage were calculated from its definition.

The maximum step voltage $V_{\text{step}}^{\max}$ for the installation under analysis is also the touch voltage V_{touch} (Equation 4).

$$V_{\text{touch}} = V_{\text{step}}^{\max}, \tag{4}$$

$$V_E^{PU} = \frac{V_E^v}{V_E^1}, \tag{5}$$

$$V_{\text{step}}^{PU} = \frac{V_{\text{step}}^v}{V_{\text{step}}^1}, \tag{6}$$

where:

V_E^v is the maximum value of the electrical potential for a given variant, in (V),

V_E^1 is the maximum value of the electrical potential for homogeneous soil (variant 1), in (V),
V_{step}^v is the maximum value of the step voltage for a given variant, in (V),
V_{step}^1 is the maximum value of the step voltage for homogeneous soil (variant 1), in (V),

Based on the results presented in Table 1, it can be concluded that the step voltage increased for the following modernization variants of the grounding system: 3, 4 and 5. Due to the assurance of the proper effectiveness of the protection against electric shock, these variants should not be used. For variant 2, the maximum step voltage value drops to 62.64 V, i.e. its value was reduced by 55.77%. In the case of variant 6, the maximum step voltage value decreases to 60.45 V. In comparison with variant 1, its value was reduced by 53.82%. During the design process, the obtained maximum values of the step/touch voltage are compared with the limit values. To determine them, the values of the shock current flow time t_s are required. A properly designed grounding system should ensure that the permissible values are not exceeded, thus eliminating the possibility of electric shock. Due to the limited paper length, the dependence on limit values of the shock voltages determined on the basis of other standards was not considered.

4. Conclusions

The paper presents the analysis results of applying conductive and insulating screens to reduce the step/touch voltage values. The maximum value of the step and touch voltage reduction is realized by the appropriate shaping of the electric field on the ground surface. Reducing the step and touch voltages improves the effectiveness of the shock protection. As the structure of a distribution network changes frequently, it may cause an increase/decrease in the earth current value. An increase in the earth current value heightens the probability of exceeding the permissible step/touch voltage values, in which case it is necessary to take action to reduce this value. As this paper proves, one of the most effective and economically viable methods of reducing step/touch voltages is the use of screens. The concept of screen application is not widely described in the literature and its effectiveness has not been proved. The aim and the main achievement of the research described in the paper is to accurately estimate the possibility of reducing the step/touch voltage by means of using screens.

This paper presents a comparison of the electric field shaping method using surface material with the method involving insulating and metallic screens. The investigations were carried out for a typical MV/LV pole substation grounding system. The value of earth fault current (single-phase short-circuit) on MV side was assumed in considerations. The single-phase short-circuit current on the LV side will have a much higher value than that assumed for the analysis by the authors. Due to the assumed linearity of the grounding system, the percentage reduction in shock voltages (step and touch) compared to variant 1 (baseline) will be the same. Based on the analysis, the best method to reduce the step/touch voltage is to use a metal screen as it limits the maximum values of the electric potential and the step/touch voltage to a large extent (by up to 50%). In addition, it causes a more even distribution of the electrical potential in the area surrounding the ground current flow point, which results in improved effectiveness of the shock protection. The only drawback of this solution is the need for adequate anti-corrosion protection of the metal screen. To protect the screen against corrosion it is possible to use galvanic protection (zinc plating) or anti-corrosive conductive paint.

The analysis of kiosk substation grounding systems is a very complex issue. The modelling of the foundation grounding system given its complexity in terms of structure and the heterogeneity of the concrete is a complex computational problem. The resistance of the foundation grounding system will influence the resulting resistance of the substation grounding. In this case, the values of touch and step voltages will be less. The paper analyzes the variant, in which there is a higher risk of negative effects of electric shock.

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