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Using interpolation method to estimation step and touch voltage in grounding system

***Abstract**. The article presents a methodology for calculating the step voltage on the ground surface above the grounding grid of an MV/LV substation. The calculations are performed by using the interpolation method based on the knowledge of the electric potential distribution. The electric potential distribution was determined for the grounding grid model using the finite element method in ANSYS program. The interpolating relationship of two variables allows the calculation of step voltage for any location of human feet.*

***Streszczenie.** W referacie przedstawiono metodykę obliczenia napięcia korkowego na powierzchni gruntu nad uziomem stacji SN/nN. Obliczenia są wykonywane za pomocą interpolacji w oparciu o znajomość rozkładu potencjału elektrycznego. Rozkład potencjału elektrycznego został wyznaczony dla modelu uziomu z wykorzystaniem metody elementów skończonych w programie ANSYS. Wyznaczona zależność interpolująca dwóch zmiennych pozwala na odliczenie napięcia krokowego dla dowolnej lokalizacji stóp człowieka. (**Wykorzystanie metody interpolacji do szacowania napięcia skokowego i dotykowego w układzie uziemiającym**)*

Keywords: grounding grid, step voltage, interpolation, finite element method
Słowa kluczowe: uziom, napięcie krokowe, interpolacja, metoda elementów skończonych

Introduction

An important aspect of substation design is reducing the risk of electric shock. This goal can be achieved by designing a grounding system that ensures that touch and step voltages are limited. The values of these voltages depend on the ground current values and the distribution of the electrical potential on the ground surface. The distribution of the electrical potential depends on the depth of the buried grounding, its design, and the resistivity of the soil.

In the case where it is not required to obtain a low resistance of grounding grid and investment costs are the decisive factor, the grounding grid is usually made as a section of steel flat bar or a vertical rod. If it is necessary to obtain a low resistance of grounding grid, it is made in the form of a grid of steel flat bars and/or vertical rods. In this case, the dimension of the grid mesh is smaller if a lower resistance of the grounding grid is required However, the value of the resistance of the grounding grid depends not only on the geometric dimensions of the ground, but also on the type of soil (its resistivity) and environmental conditions (temperature, humidity, chemical composition of the soil) [1-4]. Therefore, in purpose of proper grounding design, it is necessary to take into account the resistivity of the soil based on the results of measurements [5].

As previously mentioned, the grounding grid is an element of electric shock protection. Among other things, the values of step and touch voltages depend on their design. Step voltage is defined as the potential difference on the ground surface between points spaced by a conventional step size of 1 m [1].

For purpose of proper design of the grounding grid, and thus to meet the condition for permissible values of touch and step voltages, it is necessary to know the distribution of electrical potential on the ground surface above the buried grounding grid [1,- 3, 6 - 9].

Finding the solution to the flow field equation in a conductive environment around an electrode buried in the ground in the general case is based on determining the electric field distribution. For stationary fields, this is the solution of the Laplace equation for the electric potential V_E in the form described by equation (1).

(1) $$\nabla^2 V_E = 0$$

For simple grounding grid geometries only for a simple hemispherical grounding electrode, it is possible to solve equation (1) using the analytical method. For more complicated and close-to-real grounding grid structures with consideration of soil non-uniformity, numerical methods such as the finite element method or method of moments are used to solve equation (1) [10-14]. As a result of the calculations, the potential distribution on the ground surface is obtained with exact (only for the nodes of the discretization grid) or approximate (for the points in between according to the numerical model used) values. In this way, however, it is not possible, for example, to calculate step and touch voltage values for any location of a person's feet in the analyzed area or for any foot spacing. The article describes a solution to this problem by proposing a method to determine the step and touch voltages with an interpolation method using spline functions. Thus, the proposed method allows calculating the values of shock voltages that can occur in real conditions, where there are various and mostly unpredictable cases of entry by unauthorized persons and animals into the area protected from electric shock.

Safety criteria according to IEEE 80 standard

The grounding installation should be designed to reduce the possibility of electric shock to persons in its vicinity. The touch voltage V_{touch} and step voltage values V_{step} are used as a measure of the potential risk from the effects of the grounding system. Using the recommendations of IEEE 80 [1] it is possible to calculate the values of these voltages by analysis. The effects of electric currents on the human body depend primarily on the rms value of the electric shock current. For a fixed value of a shock voltage, the current value according to Ohm's law is dependent on the resistance of the human body. In the IEEE 80 standard [1], it is adopted at the level of 1000 Ω.

For a person standing in the close area of a grounding grid, the value of the step voltage V_{step} is the same as the value of the touch voltage V_{touch}. For touch voltage shock path is hand-legs, on the other hand, for touch voltage shock path is feet-feet. From the assumed time of the earth current flow, the permissible values of voltage are derived and they are given in a graphical or analytical form. According to the guidelines contained in [1], the limit step voltage and touch value is calculated from formula (2).

(2) $$V_{\text{step}} = V_{\text{touch}} = I_{\text{B}}(R_{\text{B}} + Z_{\text{Th}})$$

The Thevenin impedance of the accidental circuit is calculated from the formula (3), in which ρ is the soil resistivity in [Ωm] for step voltage, while for touch voltage the value of the equivalent impedance is calculated from the equation (4).

(3) $$Z_{\text{Th}} = 6 \cdot \rho$$

where ρ is the resistivity of the ground in [Ωm] for step voltage, whereas for touch voltage the value of the equivalent impedance is calculated from the equation:

(4) $$Z_{\text{Th}} = 1.5 \cdot \rho$$

Standard [1] defines the current flowing through the human body I_{B} as:

(5) $$I_{\text{B}} = \frac{k}{\sqrt{t_{\text{s}}}}$$

Where the coefficient k takes into account the effect of body weight on the value of I_{B} current. For a body weight of 50 kg, it is equal to 0.116, and for a body weight of 70 kg it is 0.57. The value of the step voltage is calculated from the equation (6).

(6) $$V_{\text{step}} = (R_{\text{B}} + 6 \cdot \rho) \cdot \frac{k}{\sqrt{t_{\text{s}}}} ,$$

The value of the touch voltage can be determined from equation (7).

(7) $$V_{\text{touch}} = (R_{\text{B}} + 1.5 \cdot \rho) \cdot \frac{k}{\sqrt{t_{\text{s}}}}$$

In the case, when applied to the surface material of different resistivity than the proper ground, appropriate replacement accidental circuit is calculated from the formula (8) for dependencies (6) and from equation (9) for dependencies (7).

(8) $$Z_{\text{Th}} = 6 \cdot \rho \cdot C_{\text{s}} ,$$

(9) $$Z_{\text{Th}} = 1.5 \cdot \rho \cdot C_{\text{s}}$$

The C_{s} factor takes into account the application of surface material. Its value is calculated in accordance with equation (10).

(10) $$C_s = 1 - \frac{0.09 \cdot \left(1 - \frac{\rho}{\rho_s}\right)}{2 \cdot h_s + 0.09}$$

For such assumptions, the limit values step and touch voltages are calculated from the relationship (11) and (12).

(11) $$V_{\text{step}} = (R_{\text{B}} + 6 \cdot \rho \cdot C_{\text{s}}) \cdot \frac{k}{\sqrt{t_{\text{s}}}}$$

(12) $$V_{\text{touch}} = (R_{\text{B}} + 1.5 \cdot \rho \cdot C_{\text{s}}) \cdot \frac{k}{\sqrt{t_{\text{s}}}}$$

The dependence of the step voltage V_{step} on the duration of the earth current flow t_{s} for selected variants is shown in Figure 1 (for human mass 50 kg) and Figure 2 (for body weight 70 kg).

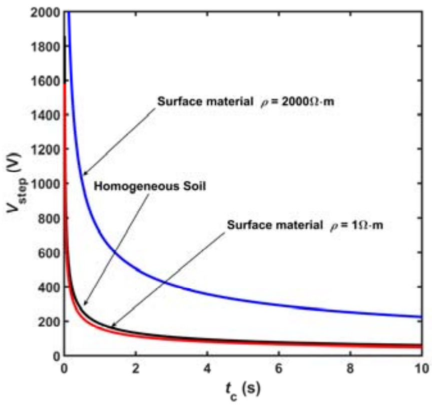

Fig. 1. Dependence of the limit value V_{step} in function t_{s} for body weight 50 kg

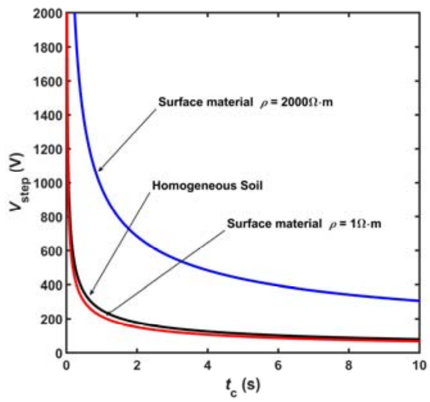

Fig. 2. Dependence of the limit value V_{step} in function ts for body weight 70 kg

Calculation of potential distribution

Step and touch voltages are calculated as a potential difference, in this case, the potential at the ground surface. As mentioned earlier, analytical methods of calculating the potential distribution can be used only for simple grounding grid geometries. For more complex structures, the best and most accurate solution is to use field methods. Therefore, for purpose of determining the potential distribution on the ground surface, the ground model was implemented in ANSYS software. A detailed description of the grounding grid model can be found in [4].

The finite element method was used to determine the potential distribution for the analyzed grounding grid. A 6.3 x 6.3 m grounding grid, buried at a depth of h = 0.8 m, was chosen for the analysis. The grounding grid was made of steel bands with the number of meshes n = 4. The point of the earth's current flow is located at the edge of the grounding grid (Fig.3 and 4). Figure 5 shows the dimensions of the analyzed grounding grid, along with an illustration of the definition of touch and step voltage. It was also assumed that the soil is homogeneous.

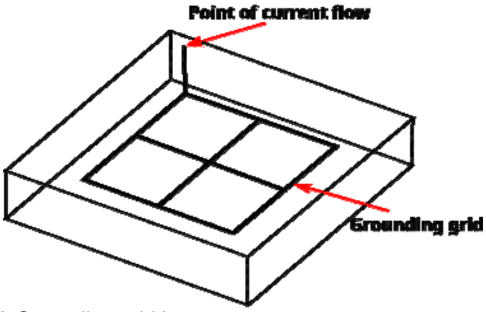

Fig.3.Grounding grid layout

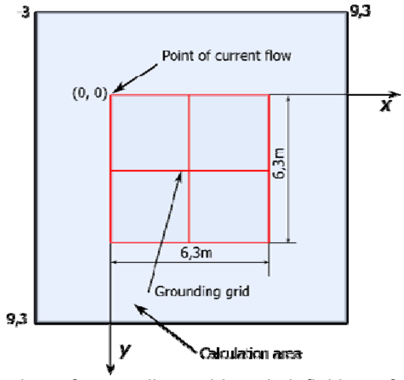

Fig.4. Dimension of grounding grid and definition of step voltage V_{step} and touch voltage V_{touch}

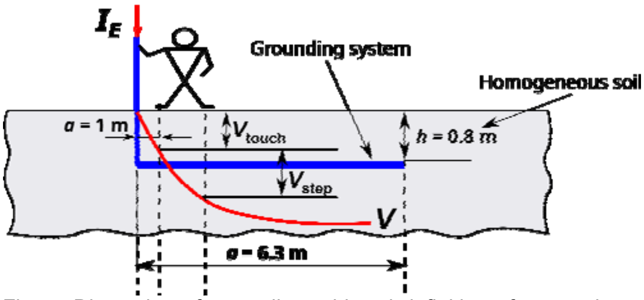

Fig. 5. Dimension of grounding grid and definition of step voltage V_{step} and touch voltage V_{touch}

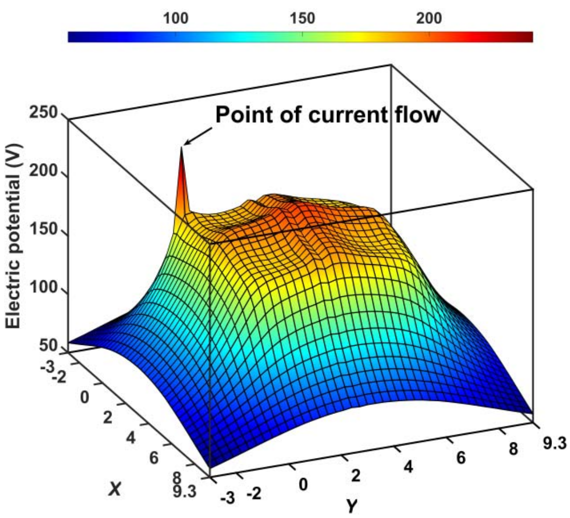

Fig.6. Electric potential distribution on the ground surface for the grounding grid in homogeneous soil

Determination of the interpolating function of the potential distribution on the ground surface

The finite element method allows the calculation of the value of a physical quantity at the nodes of the calculation mesh. The dimension of the computational mesh (number of nodes) is the result of a compromise between the accuracy and speed of calculations. Based on knowing the value of the potential at the mesh nodes, it is not possible to directly determine the value of the step voltage for any location of a person's feet - his location on the ground surface and the spacing of his feet. The solution to this problem is the interpolation method. Using this method, a function interpolating the distribution of potential on the ground surface was determined. The interpolating function is a function of two variables x and y describing the location of a point on the ground surface. The interpolating function was determined using the *Curve Fitting Toolbox* available in the Matlab environment. Due to the rather complicated shape of the potential distribution (Fig. 6), the *Interpolant - Cubic* method using splajn functions was used to determine the interpolating function. This method of interpolation is based on fitting a different cubic polynomial between each pair of data points for curves or between sets of three points for the analyzed surface. The property of this method is that the values of the root mean square error R^2 indicating the accuracy of the fit (at the mesh nodes) are equal to 1. In this way, a model was obtained, whose input parameters are the (x, y) coordinates corresponding to a given point on the ground surface. The result of the function from the *Curve Fitting Toolbox* library, which determines interpolating functions, is a created model with the appropriate structure with two input arguments. Figure 7 shows the distribution of electric potential on the ground surface using the proposed method with the marked points of the calculation mesh.

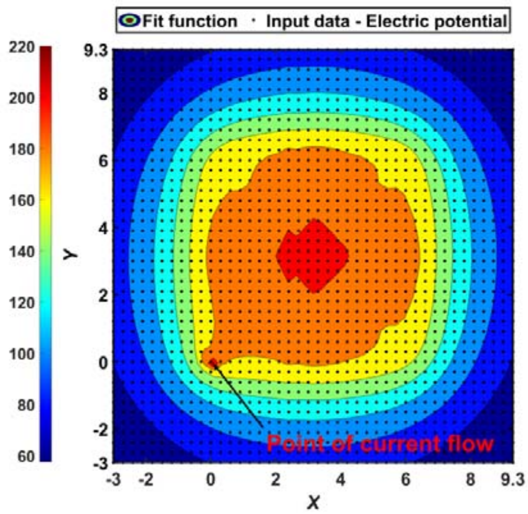

Fig.7. Graph presenting the interpolation spline function of the electric potential distribution on the ground surface for the grounding grid in homogeneous soil

The step voltage is calculated as the difference in potentials corresponding to any feet location. Using formula (15), the value of the step voltage can be calculated. The value of the step voltage is determined by taking the value of the coordinates x_1 = 0 and y_1 = 0 as illustrated by equation (16).

$$(15)\quad V_{step} = |V_1 - V_2| = |V_1(x_1, y_1) - V_2(x_2, y_2)|,$$

(16) $V_{\text{touch}} = |V_1 - V_2| = |V_1(0,0) - V_2(x_2, y_2)|$,

where: V_1 - electric potential corresponding to the location of the first foot, in [V], V_2 - electric potential corresponding to the location of the second foot, in [V], x_1, y_1 - coordinates of the first foot, x_2, y_2 - coordinates of the second foot,

The x_1, y_1, and x_2, y_2 coordinates of a given point on the ground surface result from the adopted position of the coordinate system shown in Figure 4. The current flow point for the position of the coordinate system so assumed to have coordinates (0,0). The x and y axes are located along the outer edges of the grounding grid as shown in Fig. 4. The location of the beginning of the coordinate system is a decision made at the initial stage of model construction. It seems natural and logical to choose the point of origin of the coordinate system at the point of occurrence of the highest value of the electric potential on the ground surface at the edge of the ground grid, where the point of current flow is located. In the case of a more complex grounding grid structure, with more points of current flow, there is no contraindication for the origin of the coordinate system to be located in one of them.

Conclusion

Ensuring adequate effectiveness of electric shock protection is one of the most important stages of electrical power grid design. The effectiveness of electric shock protection is significantly influenced by the grounding installation, the main element of which is the grounding grid. The grounding grid should be designed so that in the case when the ground current flows, the permissible values of touch and step voltages are not exceeded. The values of touch and step voltages depend on the distribution of electrical potential on the ground surface, which is the result of the flow of earthing current. At the design stage of the grounding grid, its shape and dimensions should be chosen to ensure the required resistance value. Moreover, the potential distribution on the ground surface above the buried grounding should be taken into account. Analytical methods can be used to calculate the potential distribution, which is used only for simple grounding grid structures assuming homogeneous soil. Numerical methods such as the finite element method should be used in the case of complex grounding grids. Numerical methods allow calculating the values of given physical quantities only at the nodes of the calculation mesh. The calculation can be made for a large number of nodes of the calculation mesh, but unfortunately, it will increase the calculation time. Knowing the values of the electric potential at the mesh nodes, the interpolation method can be used to determine the interpolating function. Using this function, the value of the potential at any point on the ground surface can be calculated. Knowing the values of the potential at the given points, it is easy to calculate the values of step and touch voltages. The developed model makes it possible to calculate the values of the above voltages for any location of human feet. This gives the ability to calculate step and touch voltages for practically any foot spacing. This is especially important when analyzing the effects of electric shock on people with small foot spacing, such as children. The developed model can also be adapted to calculate the shock voltages that animals may be exposed to. In the case of large livestock, the definition of step voltage used for humans cannot be adopted, because the distance between legs is usually greater than 1m.

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