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Optimal design of the grounding grid by FEM considering different layered soil models

Abstract. *In this paper, we use an optimization technique based on the implementation of the exponent rule of the grounding conductor arrangement and the application of the finite element method (FEM) to obtain the most efficient arrangement of the grounding grid's conductors, guaranteeing the safety regions on the ground surface defined by the maximum touch voltage. To find out the influence of the soil structure on the optimal design of the grounding grid different soil structure models were analyzed.*

Streszczenie. *W artykule przedstawiono technikę optymalizacyjną, bazującą na implementacji prawa wykładniczego w ustawieniu przewodów uziemiających oraz zastosowaniu MES dla otrzymania najbardziej efektywnego ustawienia siatki uziemiającej, gwarantującego bezpieczeństwo na powierzchni zdefiniowane przez maksymalne napięcie dotykowe. Utworzony model pozwolił zbadać wpływ struktury gleby na parametry siatki uziemiającej. (**Optymalne projektowanie siatki uziemiającej za pomocą MES w modelach o różnym uwarstwieniu gleby**)*

Keywords: finite element method, grounding grids, numerical analysis, optimal design.
Słowa kluczowe: metoda elementów skończonych, siatki uziemiające, analiza numeryczna, projekt optymalny

Introduction

The main task of the grounding system is to ensure the safe and reliable operation of electrical systems, and to guarantee a human being's safety in the situation of ground fault in the electrical system. Therefore, the most important caution in the design of grounding grids is to guarantee the safety regions which are normally defined by the maximum values of touch and step voltages prescribed by technical standards. The safety of electrical apparatus can be reached by decreasing grounding resistance and ground potential rise (GPR) of the grounding system, but the safety of people must be reached by equalizing the potential distribution on the earth surface, and reducing touch and step voltages. One of the most efficient solutions to equalize the potential distribution on the earth surface above the grounding grid, which also improves the safety of the grounding system, is the optimal arrangement of the conductors of the grounding grid. Besides the grid's geometry, the safety of the grounding grid is most of all dependent on the soil resistivity. Especially in the winter time the frozen soil leads to the change of the soil model. For that very reason, the optimal design of the grounding grid should be based on the full investigation of the actual layered soil models. To verify the influence of different soil structures on the optimal distribution of the grounding grid's conductors, we studied the electrical conditions in single-layer (uniform) and two-layer soil structure models.

It is well known that in most cases the grounding grid with fixed number of equidistantly distributed grounding grid's conductors does not assure optimal earth surface potential distribution which would ensure minimum values of touch and step voltages in the area above the buried grounding grid. Consequently, touch and step voltages can already be decreased by the unequal span arrangement among all conductors of the grounding grid. For that very reason, the objective of this work is the so-called optimal design of the grounding grid, which is nothing else but to suitably arrange the conductors of the grounding grid to equalize the potential on the earth surface. This would decrease touch and step voltages to a minimum, and ensure efficient utilization of all conductors of the grounding grid. To this purpose, we applied an optimization methodology based on the use of the grounding conductor arrangement with exponent regularity [1] and the finite element method (FEM). The design methodology of the grounding grid was analyzed with FIELD_GS software package, designed for 3D current field calculations of grounding systems by FEM, developed by the authors [2].

Numerical procedure based on FEM

The current field, caused by the fault current flowing through the grounding grid into the soil, using the electric scalar potential φ is expressed by Laplace's equation (1) and boundary conditions (2)

(1) $$\nabla\left(\left[\sigma\right]\nabla\varphi\right)=0,$$

(2) $$\varphi=0\ \ (r\rightarrow\infty),\qquad \frac{\partial\varphi}{\partial n}=0\ \ \text{(on the earth surface)}.$$

Since the FEM is a finite domain method, in our case, the spatial transformation (convenient mapping), presented in [3], is used to convert a physically unbounded solution domain into a finite domain. By applying the Galerkin's formulation of FEM, the additional transformation of the "semi-infinite space", the 3D finite elements for soil discretization, and the 1D finite elements for the grounding system discretization, the following equations are obtained.

- The equation of a twenty-node isoparametric 3D finite element (second-order hexahedron) in the transformed and non-transformed domain:

(3) $$\iiint\limits_{\Omega_{3\mathrm{D}}}\nabla N_{\mathrm{i}}\,\sigma\nabla\varphi\,\mathrm{d}\Omega=0,\qquad \varphi=\sum_{j=1}^{20}N_{\mathrm{j}}\,\varphi_{\mathrm{j}}.$$

- The equation of a three-node 1D finite element (second-order line element) in the grounding system domain:

(4) $$S_{1\mathrm{D}}\int\limits_{l_{1\mathrm{D}}}\nabla N_{\mathrm{i}}\,\sigma_{1\mathrm{D}}\,\nabla\varphi\,\mathrm{d}l=0,\qquad \varphi=\sum_{j=1}^{3}N_{\mathrm{j}}\,\varphi_{\mathrm{j}}.$$

Where: N represents interpolation function, $\Omega_{3\mathrm{D}}$ the volume of 3D finite element in the transformed and non-transformed domain. $S_{1\mathrm{D}}$, $l_{1\mathrm{D}}$, and $\sigma_{1\mathrm{D}}$ denote the cross section, the length, and the conductivity of the grounding system element modelled by 1D finite elements, respectively. The final form of the FEM equation is given by:

(5) $$\left[A\right]\left\{\varphi\right\}=\left\{B\right\}.$$

To calculate the potential in the entire region of interest, first we solve the system (5) assuming the unit potential, for example 1 V on the grounding system. For this potential, we calculate the current I that flows from the grounding system by (6), and after that, by means of (7) and the known fault current I_f, we finally calculate the absolute values of nodal potentials φ_j in the entire calculation domain:

(6) $$I = \oint_S \boldsymbol{J}\boldsymbol{n}dS$$

(7) $$\{\varphi\}_a = \{\varphi\}\frac{I_f}{I}.$$

The current I is calculated by integrating over the arbitrary surface S that embraces the grounding system. It is best to integrate over the surface that separates the transformed and non-transformed domain. $\boldsymbol{J}$ and $\boldsymbol{n}$ represent the current density throughout the S and the unit vector on the S, respectively.

Putting the appropriate nodal potential's value φ_j and nodal interpolation function N_j into the second term of (3), the electric potential V_p at any point P in the soil can be computed. In this way, the touch voltage U_T and the step voltage U_S are obtained by (8) and (9), respectively.

(8) $$U_T = \mathrm{GPR} - V_p,$$

(9) $$U_S = V_{p2} - V_{p1}.$$

Where: V_{p1} and V_{p2} are the earth surface potentials at two arbitrary points separated by 1 m.

Description of the optimization problem

As already mentioned, the design of grounding grids is dictated by safety considerations. The main purpose is the minimization of possible body currents in persons working or walking around and within the electrical objects. Ordinarily, the touch voltage is higher than the step voltage, but the limit of the touch voltage postulated by IEEE Std. 80-2000 [4] is smaller then the maximum permissible value of the step voltage. Consequently, if the touch voltage is in the safe region, then the step voltage is in the safe region too. Therefore, in our proposed methodology, the safety considerations are translated to the minimization of the maximum touch voltage. According to [5], the maximum touch voltage occurs at a point located approximately above the centre of the corner mesh of the regular grounding grid. Many times, however, grounding grids are irregular. In these cases, it is not obvious where the maximum touch voltages will occur. In general, the maximum touch voltages will occur near the extremities (the centre and the edge) of the grounding grid. Therefore, to determine the maximum touch voltage in an irregular grounding grid, we focus our attention on the values of the computed touch voltage profile along the diagonal of the grounding grid, especially at the points located approximately above the centres of the meshes near the extremities.

The touch voltage value depends on the soil resistivity and the density of conductors used in the grid. For rectangular grids, this density can be obtained by the number of conductors in the *x* and *y* directions and by the compression ratio C ($0 < C \le 1$) which defines the linear or exponent distribution of these conductors. If $C = 1$, the distribution of conductors is linear (the grounding grid is designed with an equal conductor span). If $C < 1$, this distribution is exponent (the conductor span decreases gradually from the centre to the side of the grounding grid).

According to the above definition, when the side length of the grounding grid L and the conductor number N are determined, if we select C, the central conductor span d_{max} can be calculated by (10) or (11), and the conductor span d_i between any two grounding conductors in a side of the grounding grid can be calculated by (12). Figure 1 shows the meaning of these geometric parameters.

(10) $$d_{max} = \frac{L(1-C)}{1+C-2C^{(N/2+1)}}, \quad (N \text{ is even})$$

(11) $$d_{max} = \frac{L(1-C)}{2\left(1-C^{(N-1)/2}\right)}, \quad (N \text{ is odd})$$

(12) $$d_i = d_{max}C^i, \quad (i = 0 \text{ to } m)$$

If N in one side is even, then $m = N/2 - 1$; if N is odd, then $m = (N - 1)/2 - 1$. As shown in Figure 1, there are two central conductor spans if the conductor number N of the grounding grid in one side is odd. If C is selected, only a fixed grounding grid structure can be determined. For a square grounding grid, only one compression ratio should be determined, but for the rectangular grounding grid two compression ratios should be determined.

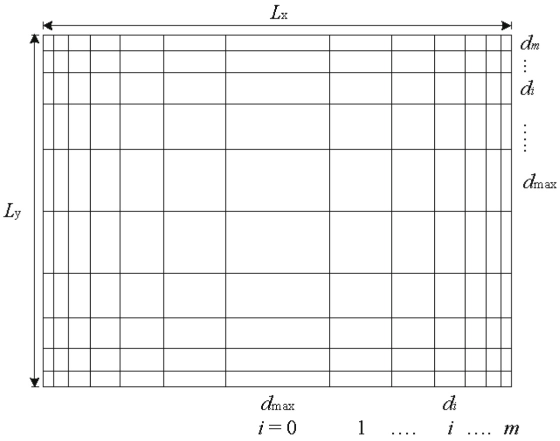

Fig.1. Scheme of the grounding grid arranged by the exponent rule

The optimal design process of the grounding grid proceeds in an iterative fashion. First a design at $C = 1$ is assumed and then an analysis of the design is performed to determine maximum touch voltage. After the analysis the modifications to the grounding grid are made and the procedure is repeated for different values of C. After the analysis of the obtained results, for the optimal design, the grounding conductor arrangement with the minimum value of maximum touch voltage is selected. Details about the formulation of the proposed optimal design methodology are presented below.

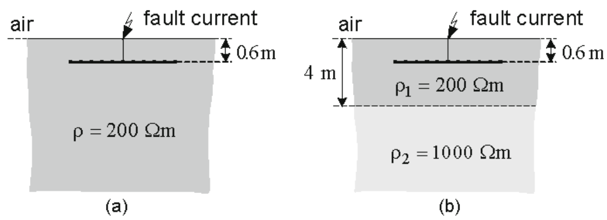

Fig.2. Soil model of the uniform soil (a) and of the two-layer soil (b)

Influence of different soil layers on the optimal design of the grounding grid

In our application, the design procedure of 100 m by 100 m grounding grid ($L_x = L_y = 100$ m), which consists of 11 conductors in each direction ($N_x = N_y = 11$), is presented. As illustrated in Figure 2, the grounding grid is buried 0.6 m below the earth surface in the uniform soil and in the two-layer soil. The maximum grid current is assumed to be

1000 A, and the value of C varies between 0.4 and 1. For these parameters, the central conductor span d_{max} can be computed by (11), and the conductor span d_i between any two grounding conductors in both sides of the grounding grid can be computed by (12). For each C, we must compute the density of conductors used in the grid and the value of the maximum touch voltage on the main diagonal.

Subdividing the interval between the limits of parameter C into seven points, seven different configurations of the grounding grid were obtained. The computed values of spans between the conductors of the grounding grid are presented in Table 1. After obtaining the grounding grid's conductor arrangement, for each configuration of the grounding grid, the current field was calculated with FIELD_GS software package. In the post-processing stage, the maximum values of touch voltages near the centre ($U_{T\text{-}cent}$) and near the edge ($U_{T\text{-}edge}$) of the grounding grid were evaluated. The optimal solution was given by the compression ratio at which the minimum value of both maximum touch voltages ($U_{T\text{-}cent}$ and $U_{T\text{-}edge}$) was obtained. We define this C as the optimum compression ratio (OCR) if the grounding grid is designed under this compression ratio. As shown in Figures 3 and 4, the OCR was found in the intersection of both response functions.

Table 1. Computed values of conductor spans

C	d_{max} [m]	d_1 [m]	d_2 [m]	d_3 [m]	d_4 [m]
0.4	30.31	12.12	4.85	1.94	0.78
0.5	25.81	12.9	6.45	3.23	1.61
0.6	21.69	13.01	7.81	4.68	2.81
0.7	18,03	12.62	8.83	6.18	4.33
0.8	14.87	11.9	9.51	7.62	6.1
0.9	12.21	10.99	9.89	8.9	8.01
1	10	10	10	10	10

A. Optimal design of the grounding grid in uniform soil

The distributions of $U_{T\text{-}cent}$ and $U_{T\text{-}edge}$ as a function of C in case of the grounding grid buried in the uniform soil with the resistivity of 200 Ω·m (Figure 2a) are shown in Figure 3. From these response functions, the optimal value of C was found at OCR = 0.815. Applying the value of OCR into the equations (11) and (12), the following conductor spans are computed, respectively: d_{max} = 14.44 m, d_1 = 11.77 m, d_2 = 9.59 m, d_3 = 7.82 m, and d_4 = 6.37 m.

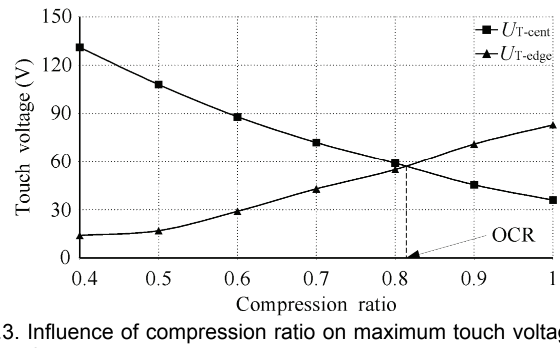

Fig.3. Influence of compression ratio on maximum touch voltage in the uniform soil

B. Optimal design of the grounding grid in two-layer soil

From the relationships between the touch voltages and the compression ratios in Figure 4, it can be shown that in case of the grounding grid in double-layered soil model with the upper-layer resistivity (from earth surface to the depth of 4 m) of 200 Ω·m and bottom-layer resistivity of 1000 Ω·m (Figure 2b) the maximum value of touch voltage reaches its minimum at OCR = 0.71. The values obtained at the end of the optimization process are: d_{max} = 17.69 m, d_1 = 12.56 m, d_2 = 8.92 m, d_3 = 6.33 m, and d_4 = 4.5 m.

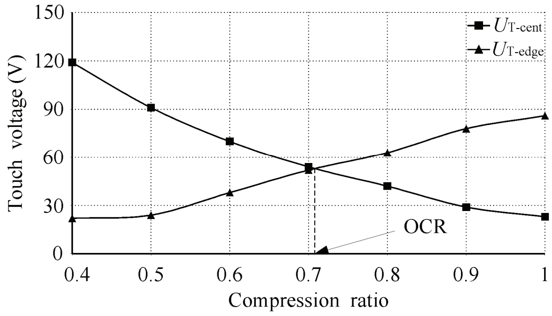

Fig.4. Influence of C on maximum touch voltage in the twolayer soil

Comparing Figure 4 with Figure 3, one can see that the value of OCR obtained in case of the two-layer soil model differs from the OCR value obtained in case of the uniform soil model. Since the influence of different soil models on the value of OCR is different, the optimal design procedure for each new structure of the soil should be repeated over and over again. This is to certify that the search for the optimal design of the grounding grid is a repetitive process which strongly depends upon the structure of the soil.

Conclusion

The objective of this work is to obtain the most efficient arrangement of the conductors of the grounding grid, but at the same time avoiding the violation of the safety criteria defined by the maximum touch voltage. The design procedure is iterative, based on analysis and subsequent modification of the grounding grid until the optimal design of the grounding grid is obtained.

As shown in Figures 3 and 4, the grounding conductor arrangement with exponent regularity is obviously reasonable. This arrangement not only decreases the potential on the earth surface, but is also certified as a safe and economic design method. Moreover, one can make sure how important it is to evaluate the actual soil structure model correctly in the optimal design of the grounding grid.

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