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Study on a Standard for Grounding Systems Realization

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Abstract: Grounding systems of objects inside power facilities are very often realized as structures consisting of protective electrodes' system placed in the object foundation, and neutral electrodes' system placed at a specified distance from the object. Official standards and publications recommend a minimal value for the distance between the protective and the neutral part of grounding structures, so that the influence of one on another can be neglected. We analyze several practical implementations of grounding structures and demonstrate that the minimal distance is actually much smaller than that recommended by the standards.

Keywords: Grounding electrode, Grounding system, Method of Moments, Power station, Resistance.

1 Introduction

The power stations` grounding system usually consists of the protective and the neutral electrodes' system. Official publications as [1] include standards dealing with the recommended value of the minimal distance between those two parts of the grounding system. It is assumed that at distances larger that recommended, the mutual (undesirable) influence between the parts of the grounding system can be neglected. This practically means that less than 40% of the total voltage is transmitted between two electrode systems. The degree of this influence corresponds to the ratio between the values of the mutual resistance between the systems and the total resistance of the grounding system.

The grounding system has been analyzed using the Method of Moments [2], and the approach applied in [3 – 13]. Quasi-stationary regime and constant leakage currents from electrodes' surfaces are assumed. The proposed approach can be also applied to other wire electrodes' systems. Because of that, the procedure is first introduced for two wire electrodes' system. Afterwards, the method is applied on analysis of particular typical grounding system with the protective electrodes' system consisting of a square-shaped contour and straight wires, and the neutral electrodes' system formed of three straight wires.

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Based on the obtained results, one can conclude that distances between two parts of the grounding system may have smaller values than the recommended ones. Note that official standards do not provide rationale for choosing the recommended values for minimal distances.

The aim of this paper is not an ambition to unconditionally change recommended distances. The idea is to put this question into the public and try to get somewhat more detailed explanation that would justify the recommended values.

2 Theoretical Background

2.1 General problem

We consider a system consisting of the total of $N = N_1 + N_2$ linear conductors, where N_1 conductors are fed by common isolated earthing conductor with a current I_{g1}, and N_2 conductors are fed with common supplying current I_{g2}. The system is depicted in Fig. 1.

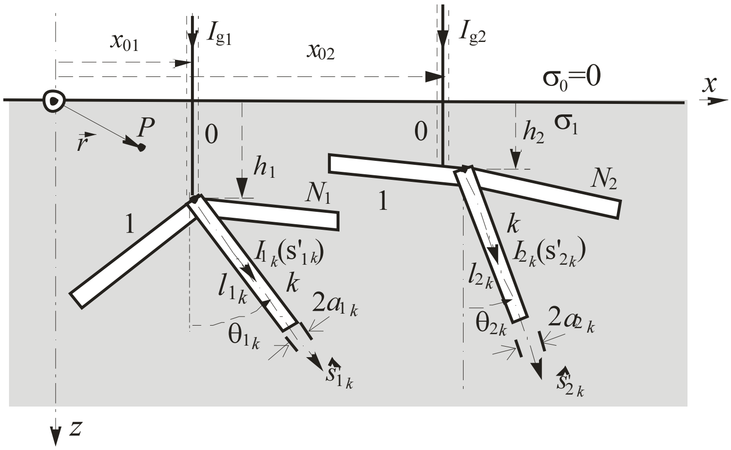

Fig. 1 – *Illustration of two coupled linear grounding systems.*

The linear ground conductors of length l_{ik} and circular cross-section radius a_{ik}, $a_{ik} << l_{ik}$, $k = 1,2,...N_i$, $i = 1,2$ are placed in homogeneous ground.

The ground is treated as isotropic media having known electrical conductivity σ_1. We use the following reflection and transmission coefficients:

$$R_{10} = (\sigma_1 - \sigma_0)/(\sigma_1 + \sigma_0) \tag{1}$$

and

$$T_{10} = 2\sigma_1/(\sigma_1 + \sigma_0) \tag{2}$$

are reflection and transmission coefficients, respectively.

Electric scalar potential of the system at the ground point P, defined by vector $\vec{r}$, is

$$\phi_1(\vec{r}) = \phi_{10}(\vec{r}) + \phi_{11}(\vec{r}) =$$
$$= \frac{1}{4\pi\sigma_1}\left[\sum_{i=1}^{2}\frac{T_{10}I_{gi}}{\left|\vec{r}-x_{0i}\hat{x}\right|} + \sum_{i=1}^{2}\sum_{k=0}^{N_i}\int_{s'_{ki}=0}^{l_{ki}} I_{ik}(s'_{ik})\frac{\partial}{\partial s'_{ik}}K(\vec{r},s'_{ik})\,\mathrm{d}s'_{ik}\right], \tag{3}$$

where x_{0i} , $i = 1,2$ denote the positions of the supplying points at the ground surface, $I_{ik}(s'_{ik})$ is longitudinal current distribution and $K(\vec{r},s'_{ik})$ is a kernel of the form,

$$K(\vec{r},s'_{ik}) = (1/r_{1k}) + (R_{10}/r_{2k})\,. \tag{4}$$

In (2), r_{1k} and r_{2k} are distances between the point P and conductor current element, and its image in modified flat mirror, respectively.

Matching the electric scalar potential value (1) at the conductors surface points P_n , $\phi_1 \cong U_n$, the following system of integral equations is obtained:

$$U_n = \frac{1}{4\pi\sigma_1}\left\{\sum_{i=1}^{2}\sum_{k=1}^{N_i}\left[I_{ik}(l_{ik})K(s_n,l_{ik}) - \int_{s'_k=0}^{l_k} I'_{ik}(s'_{ik})K(s_n,s'_{ik})\,\mathrm{d}s'_{ik}\right]\right\},\quad n = 1,2\,, \tag{5}$$

where: $I_{ik}(l_{ik})$ are currents at endings of ground electrodes, $I'_{ik}(s'_{ik}) = -\partial I_{ik} / \partial s'_{ik}$ are leakage currents density per unit length and s_n denotes distance between the matching point P_n at the n-th conductor surface and its origin.

The solution of the equation system (5) is current distribution along the conductors $I_{ik}(s'_{ik})$, $k = 1,2,...N_i$, $i = 1,2$, where feeding currents satisfy conditions

$$\sum_{k=1}^{N_i} I_{ik}(0) = I_{gi}\,,\quad i = 1,2\,. \tag{6}$$

Assuming polynomial form of the current distribution [14]:

$$I_{ik}(s'_{ik}) = \sum_{m=0}^{M_k} I_{ikm}\left(s'_{ik} / l_{ik}\right)^m,\quad k = 1,2,...N_i,\quad i = 1,2\,, \tag{7}$$

where I_{km} , $k = 1,2,...N_i$, $m = 0,1,...M_k$ are unknown coefficients (dimensionally equal to currents), the system (5) transforms into

$$U_n = \frac{1}{4\pi\underline{\sigma}_1}\left\{\sum_{i=1}^{2}\sum_{k=1}^{N_i}\sum_{m=0}^{M_k} I_{ikm}\left[K(s_n,l_{ik}) - \frac{m}{l_{ik}}\int_{s'_{ik}=0}^{l_{ik}}\left(\frac{s'_{ik}}{l_{ik}}\right)^{m-1} K(s_n,s'_{ik})\,\mathrm{d}s'_{ik}\right\},\quad n = 1,2. \tag{8}$$

The total number of unknown coefficients in (8) is $N_u = \sum_{i=1}^{2}\sum_{k=1}^{N_i}(M_k+1)$ and there are $N_1 + N_2$ boundary conditions for currents:

$$I_{ik}(s'_{ik} = l_{ik}) = 0\,, \quad k = 1,2,...N_i\,, \quad i = 1,2\,. \tag{9}$$

The rest of the linear equations is formed by matching voltages from (8) at the conductors surfaces points defined with

$$s_{nj} = \frac{j}{M_k+1} l_{ik}\,, \quad j = 1,2,...M_k\,, \quad k = 1,2,...N_i\,, \quad i = 1,2\,. \tag{10}$$

After solving the system given with (8) and (9), the coefficients in (7), i.e., current distribution along the conductors are obtained.

The equation system (8) with conditions (9) is solved for two regimes of feeding: symmetric ($U_1 = U_2 = U_s = 1$ V) and anti-symmetric ($U_1 = U_2 = U_a = -1$ V). After determining coefficients in equation (7) the feeding currents $I_{gk}^{s/a}$, $k = 1,2$ are obtained using equation (6). Labels "s/a" denote solution for the currents corresponding to the supplying potential U_s – symmetric, i.e. U_a – anti-symmetric.

In the general case the following relations between electrodes voltage and their feeding currents exist:

$$U_1 = R_{11}I_{g1} + R_{12}I_{g2}\,, \quad U_2 = R_{21}I_{g1} + R_{22}I_{g2}\,. \tag{11}$$

In (9), R_{11} and R_{22} are self-impedances of the electrode system 1 and 2, while $R_{12} = R_{21}$ are mutual-impedances between two systems. "*R*" parameters represent integral grounding system characteristics and measure of mutual influence level between coupled wire electrodes systems

2.2 Application on one standard grounding system

The analyzed grounding system, presented in Fig. 2, is placed in the linear, isotropic and homogeneous ground of specific conductivity σ_1, while specific conductivity of the air is $\sigma_0 \approx 0$. Consequently, $R_{10} = 1$ and $T_{10} = 2$. The protective and the neutral electrode structures are formed of $N_1 = 8$ straight wire electrodes, and of $N_2 = 6$ conductors, respectively. The feeding currents corresponding to these two components of the grounding system are I_{g1} and I_{g2}, respectively. It is assumed that leakage current is constant, i.e. in (7) is $M_1 = M_2 = 1$.

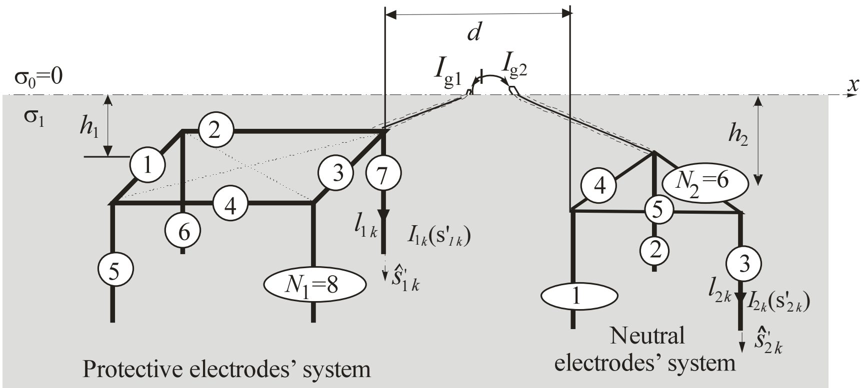

Fig. 2 – *Grounding system.*

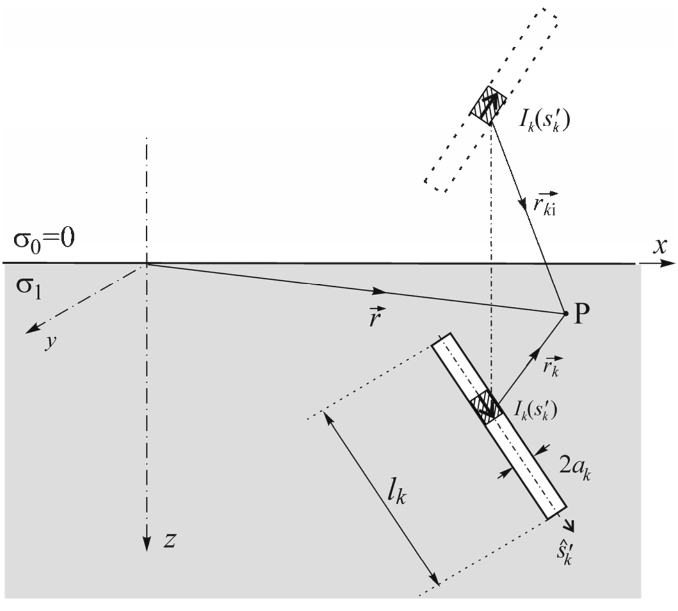

Fig. 3 – *Schema for the electric scalar potential expression* (12).

The potential of the system at the arbitrary point P in the ground (Fig. 3) can be expressed as

$$\phi(\vec{r}) = \sum_{j=1}^{2}\sum_{k=1}^{N_j} \frac{I_{jk}}{4\pi\sigma_1 l_{jk}} \int_{l_{jk}} \left(\frac{1}{r_k} + \frac{1}{r_{k\mathrm{i}}}\right) \mathrm{d}\, s'_{jk} \tag{12}$$

where l_{jk}, and I_{jk}, $j = 1,2$, $k = 1,2,\ldots N_j$ are length of the wires and total leakage currents of the wires, respectively. Also in (1), r_k and $r_{k\mathrm{i}}$ denote distances between the current element and its image from the field point, respectively, as it has been shown in Fig. 2. Applying the Method of Moments [2] and matching the potential value at points on the protective electrodes' system wires defined by field vectors $\vec{r}_{pn}$, $n=1,2,...N_1$, and at points on the neutral electrodes' system $\vec{r}_{pm}$, $m=1,2,...N_2$, the following system of integral equations is formed

$$\begin{aligned} \phi(\vec{r}=\vec{r}_{pn}) &\cong U_1, \quad n=1,2,...N_1, \\ \phi(\vec{r}=\vec{r}_{pm}) &\cong U_2, \quad m=1,2,...N_2. \end{aligned} \tag{13}$$

Total feeding currents of the parts of the grounding systems are

$$I_{g1}=\sum_{k=1}^{N_1} I_{1k} \text{ and } I_{g2}=\sum_{k=1}^{N_2} I_{2k}. \tag{14}$$

Based on these solutions, the solution for self- (R_{11} and R_{22}) and mutual-resistances (R_{12} and R_{21}) of the electrode system are obtained (11).

If the electrodes are connected, i.e. they form a single grounding system, by substituting U_1=–U_2=1 V in (13), grounding resistance can be determined as

$$R_{\mathrm{T}}=1/(I_{\mathrm{g}1}+I_{\mathrm{g}2})=\frac{R_{11}R_{22}-R_{12}R_{21}}{R_{11}+R_{22}-R_{12}-R_{21}}. \tag{15}$$

3 Numerical Results

The grounding system consisting of the protective and the neutral electrodes' systems from Fig. 2 is analyzed. The protective system is formed of four wires of length l_n=5 m, n=1,...,4, and four vertical wires of length l_n=3 m, n=5,...,8. The neutral system consists of three vertical wire electrodes of length l_m=3 m, m=1,2,3, mutually connected with three horizontal wires of length l_m=10 m, m=4,5,6. It is maximal recommended value for the distance between vertical conductors of neutral electrodes' system according to [1].

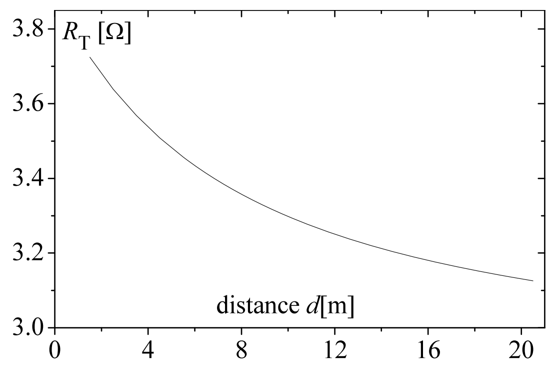

Fig. 4 – *Total resistance of the grounding system from* Fig. 2 *vs. distance d.*

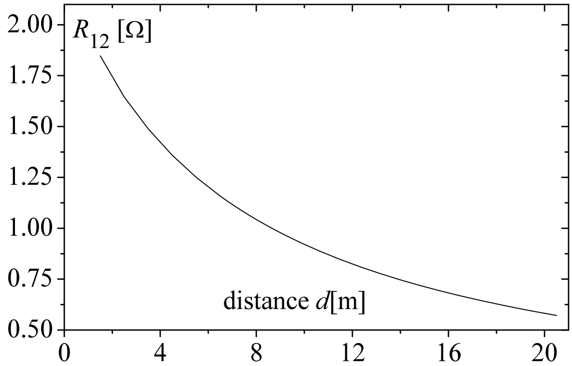

Fig. 5 – *Mutual resistance of the grounding system from* Fig. 2 *vs. distance d.*

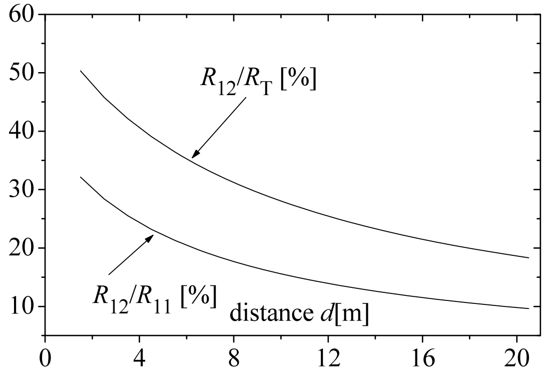

Fig. 6 – *The ratios between mutual resistance and self-resistance of protective electrodes` system, i.e. the total resistance of the grounding system vs. distance d.* (Fig. 2).

Both systems are placed at depth $h_1 = h_2 = 0.8$ m. The radius of the wires $n = 1,...,8$ and $m = 1,2,3$ is 31.5 mm. The conductors $m = 4,5,6$ are strip conductors (FeZn) of cross-section (30×4) mm^2. Their equivalent radius, determined using the procedure from [5] is 9.7 mm. The values correspond to the grounding system realized according to [1]. The value of $\sigma_1 = 0.001$ S/m is adopted for the specific conductivity of the ground [15].

The total system resistance R_T and the mutual resistance between the systems R_{12} versus the distance between protective and neutral systems d are shown in Figs. 4 and 5 respectively.

The ratios between mutual-resistance R_{12} and self-resistance of the of the protective electrodes' system R_{11} i.e. total system resistance versus the distance between protective and neutral systems *d*, are shown in Fig. 6. The results given in Fig. 6 do not depend on the specific conductivity value, since the ratios between the obtained values are presented. One can conclude that desirable ratio of the influence (less than 40 %) exists for the distances much smaller than recommended 20 m [1].

4 Conclusion

The characteristics of a typical grounding system formed of the protective and the neutral electrodes' system are determined in the paper. The mutual influence of those two electrode systems is particularly analyzed. It has been shown that this influence is satisfactory small for the distances that are smaller than the ones recommended in publications available to authors. It can be assumed that authors of this publication took some other problem aspects into consideration, since simple numerical analysis based on usual procedures gave above mentioned results.

5 Acknowledgment

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