Comparison of different models for determining the grounding rod resistance

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Calculation methods, simulations and experimental measurement are carried out in the paper. The procedures include Method of Moments (MoM), empirical engineering equations for design of horizontal and vertical grounding rod electrodes, simulations and experimental validation. Calculation of grounding rod electrode resistance was performed with different empirical formulas. Obtained results by using these empirical equations that are used to estimate a grounding grid resistance in order to obtain required parameters such as touch and step voltage, maximum current, minimum conductor size and electrode size and maximum fault current level, are compared with simulation and experimental results. 3D simulation was performed in case of rod electrode with actual dimension and for this purpose FEM (Finite Element Method) - COMSOL software package is used and the potential distribution and resistances have been determined.

Introduction

The grounding rod electrode is one of the most commonly used earthing in the construction of grounding systems. As a very important part of each grounding system, it has a very wide intention. All grounding systems, regardless of the shape and design, have the same purpose and that is leading the fault current into the surrounding soil, safely and without consequences for the working environment. Grounding system of every power substation is performed by using rod electrodes connected together. Number of rod electrodes that constitute the grid, depends on the required value of the grounding system resistance. Because of that, internal meshes are performed in order to decrease grounding resistance. Rod electrode is of extremely significance for grounding system operation i.e. to provide proper function of electrical system, but to ensure the protection of people working in the vicinity of substation and equipment against danger of electric shock during the faults. Because of that it’s very important to determine the grounding rod electrode resistance.

Procedure for determination of rod electrode resistance based on quasi-stationary approach, includes using the Method of Moments (MoM) [1], different empirical expressions for evaluation of rod electrode resistance, as well as Finite Element Method (FEM) based software package, COMSOL [2] and experimental validation.

The results obtained by using different empirical formulas are accurate within certain cases. Those formulas have some safety margins, due to usually long life time and aging effects.

Method of Moments

Applying quasistationary image theory and approach presented in [3], it is possible to analyze the rod ground electrode with length l and radius of cross-section a, ($a \ll l$), placed in homogenous soil of specific conductivity σ, Fig. 1. Specific conductivity of the air is labeled with σ_0 ($\sigma_0 \cong 0$).

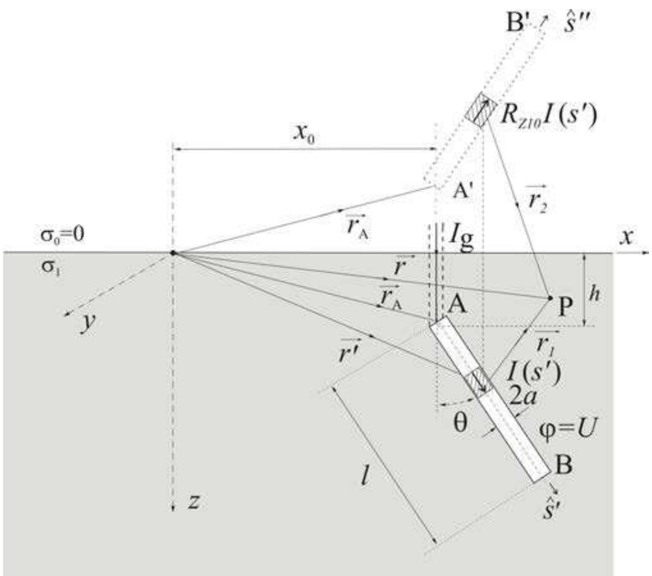


Fig.1. Rod ground electrode.

After applying the quasistationary image theory, potential in vicinity of electrode is defined with following expression, [3]

$$\varphi(\vec{r}) = \frac{1}{4\pi\sigma} \cdot \frac{T_{z10} I_g}{|\vec{r} - x_0 \hat{x}|} + \int_{s'}^{l} \frac{I(s')}{4\pi\sigma} \frac{\partial}{\partial s'_k} \left(\frac{1}{r_1} + \frac{R_{z10}}{r_2} \right) \mathrm{d}s' \quad (1)$$

where R_{z10} and T_{z10} are coefficients of reflection and transmission respectively and their relation is given by following equation:

$$R_{z10} = \frac{\sigma - \sigma_0}{\sigma + \sigma_0} \cong 1, T_{z10} = 1 + R_{z10} = \frac{2\sigma}{\sigma + \sigma_0} \cong 2 \quad (2)$$

Applying partial integration, assuming that the wire is enough thin ($a << l$) and taking into consideration expressions (2), the expression for the potential gets the form:

$$\varphi(\vec{r}) = \frac{1}{4\pi\sigma} \int_{l} I_{\text{leak}}(s') \left(\frac{1}{r_1} + \frac{1}{r_2} \right) \mathrm{d}s' \quad (3)$$

where $I_{\text{leak}}(s') = -\partial I(s')/\partial s'$ is longitudinal leakage current density.

If it is assumed that the leakage current from the electrode surface is constant $I_{\text{leak}}(s') = I_{\text{g}}/l$, potential can be obtained from the following equation:

$$\varphi(\vec{r}) = \frac{I_{\text{g}}}{4\pi\sigma l} \int_{l} \left(\frac{1}{r_1} + \frac{1}{r_2} \right) \mathrm{d}s' \quad (4)$$

In (3)-(4), r_1 and r_2 are distances from the conductor element, i.e. its image in the flat mirror from the point where the potential is determined, respectively, Fig. 1.

Applying Point Matching Method (PMM), the potential value is matched at the middle of the rod (matching point is defined with field vector $\vec{r} = (l/2)\hat{s}'$), the following equation is formed:

$$\varphi(\vec{r}) \cong U \quad (5)$$

The grounding system resistance can be determined as:

$$R_{\text{g}} = U/I_{\text{g}}. \quad (6)$$

Empirical expressions for calculating rod electrode resistance

Different empirical equations are used to estimate a grounding grid resistance in order to obtain required parameters such as touch and step voltage, maximum current, minimum conductor size and electrode size and maximum fault current level.

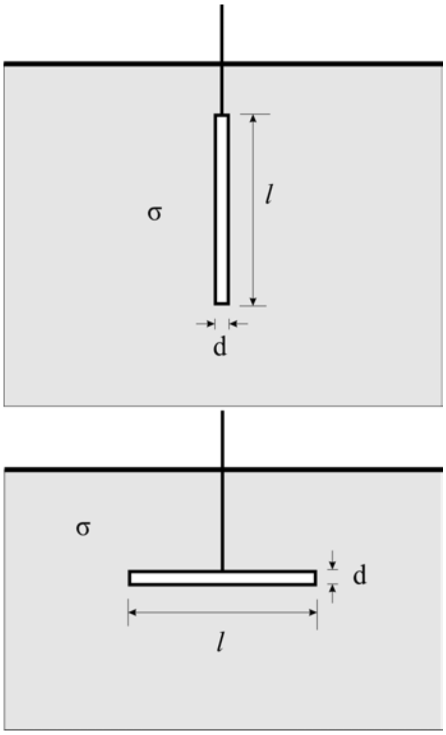


Fig.2. Vertical and horizontal ground rod electrode.

There are empirical equations based on experimental experience which can be used for checking and sizing of the rod electrode from Fig. 2 in the phase of its construction and experimental verification of its accuracy [4], [5].

Resistance of vertically placed electrode can be approximately calculated by using expression:

$$R = \frac{1}{2\pi\sigma l} \ln \frac{4l}{d} \quad (7)$$

The approximate expression for resistance of horizontally placed ground electrode is given as:

$$R = \frac{1}{2\sigma\pi l} \ln \frac{2l}{d} \quad (8)$$

Experimental results

For measurement of the resistance of rod electrode (Fig. 2) Wenner method has been used. Dimension of rod electrode is given in Table 1.

Table 1

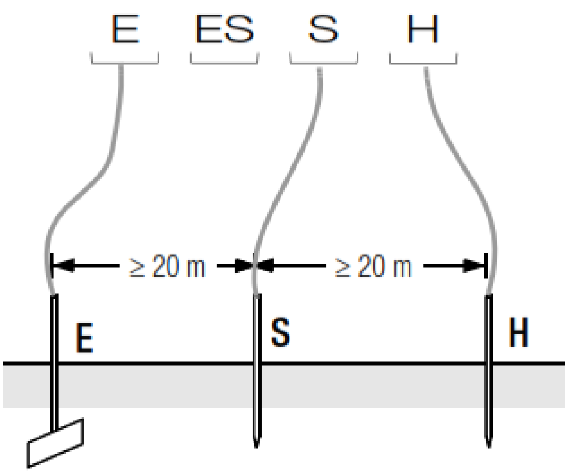
Dimension of rod electrode

Length [m]	Diameter [m]
1.6	**0.035**

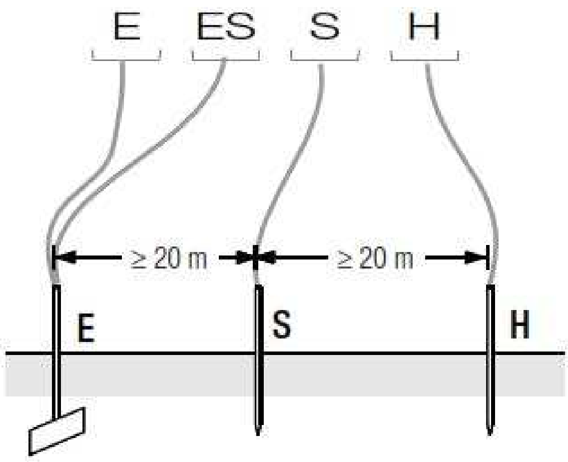
For resistance measurement of this kind of ground electrode, GEOHM C earth tester has been used. Measuring was performed in accordance with instructions described in detail in [6]. Process of measuring is illustrated in Figs. 4 a-b.

Measurement cables must be well insulated in order to avoid shunting. In order to reduce coupling influence to a minimum, measurement cables should neither cross one another, nor should they run parallel to each other over long distances. Experimental measurement of rod electrode resistance is shown in Fig. 8. Measuring was performed in accordance with instructions described in detail in [6].

Fig.3. Rod electrode.



a)



b)

Fig.4. Measuring earthling resistance with a) Three wire test setup; b) Four wire test setup.

Fig.5. Experimental measuring of rod electrode resistance.

Analysis based on FEM application

In this chapter, the results obtained using FEM base program package COMSOL, are presented. COMSOL is a software package for various physics and engineering applications, especially coupled phenomena, or multiphysics. For the purpose of comparative analysis, AC/DC module is used with “Electric Currents” interface.

The geometry of the grounding systems is modeled according to realistic geometry of previously described grounding system (Fig. 3). It should be noted that surrounding soil practically has infinite dimensions. Thus, it is modeled with a domain whose dimensions are much greater than dimensions of the grounding system with boundary conditions set to be zero potential.

Since for realized grounding systems, the soil specific conductivity varies with season weather changes inducing changing of step and touch voltage, simulation and comparative analysis were performed for different values of surrounding soil electrical conductivity [0.001, 0.01, 0.1] S/m. Resistances of the electrodes versus electrical conductivity of surrounding soil are given in Table 2.

Table 2

Electrode resistance versus the surrounding soil conductivity

C		Horizontal position	
σ [S/m]	R_g [Ω]	σ [S/m]	R_g [Ω]
0.001	440.1	0.001	474.92
0.01	43.98	0.01	47.52
0.1	4.4	0.1	4.749

It is also interesting to observe the current density stream lines for rod electrode and the potential distribution in vicinity of electrode for vertical and horizontal position which are shown on Figs 6 and 7 respectively.

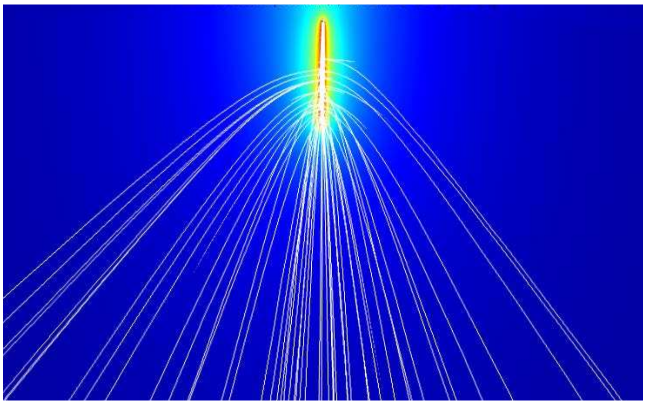


Fig.6. Current and potential distribution of vertical rod electrode.

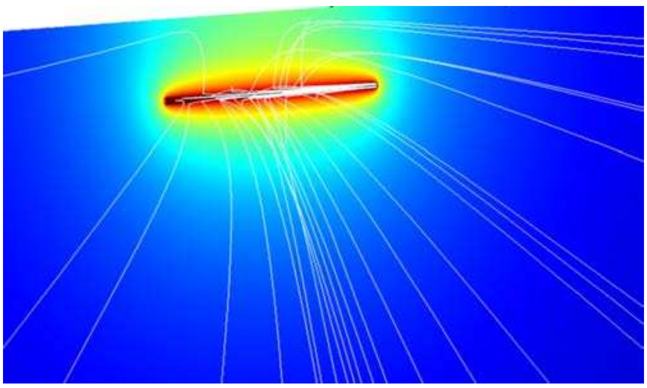


Fig.7 Current and potential distribution of horizontal rod electrode.

The potential distribution above the ground surface for both position of rod electrode is shown in Figs 8-9.

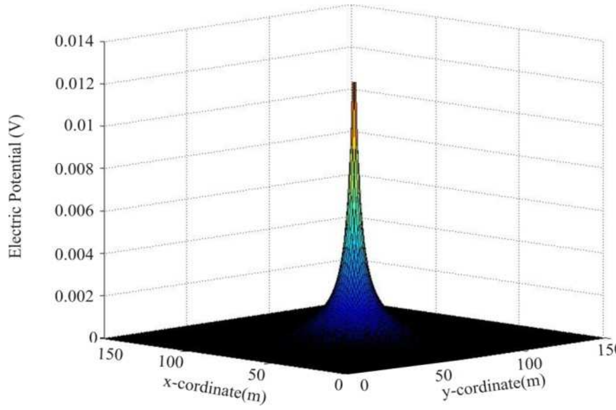


Fig.8. The potential distribution at the ground surface of vertical rod electrode.

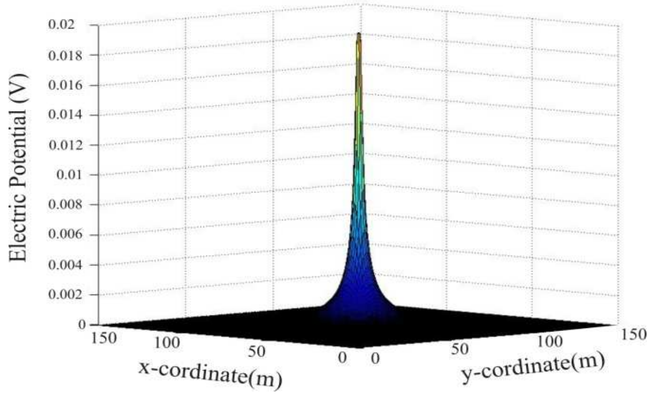


Fig.9. The potential distribution at the ground surface of horizontal rod electrode,

Comparison of the results

The procedure of Method of Moments and the previously described empirical equations are applied in resistance calculation of rod electrode of geometry parameters selected according to realistic geometry with parameters shown in Table I. The rod electrode is placed in homogeneous ground of specific conductivity.

The results obtained using Method of Moments, by applying empirical equations, FEM software package-COMSOL and results obtained by experimental measurement are compared and shown in Table 3.

Table 3

Comparison of the results for Rg [Ω]

Method	Vertical rod	Horizontal rod
MoM	39.98	52.316
COMSOL	43.98	47.52
Empirical expression	51.83	44.94
Experimental results	38.5	50

Conclusion

Analysis of the grounding rod electrode resistance for different positions is carried out in this paper. Different methods and empirical formulas and experimental measurement are used in order to obtaining and comparing results.

Results obtained by experimental measuring are compared with those ones obtained using MoM, FEM software package-COMSOL and empirical engineering equations used in practice for designing grounding systems [4], [5] in order of their validation and possible improvements.

Certain expressions that are proposed in this paper give slightly higher values of resistance. This is also expected, because of certain safety margins, aging effects etc.

The rod electrode resistance calculated using the proposed formula is very accurate when compared to an experimental measurement.

The method and empirical equations previously described provide exceptional assistance to engineers when it is necessary to check the parameters of the grounding system and perform evaluation of grounding electrode resistance before implementation of grounding system as well as in the later phase of testing its efficiency and safety.

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