Particular Grounding Systems Analysis using FEM Models

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Abstract—The aim of this work is to study the actual behavior of grounding systems using the Finite Element Method (FEM) in the Ansys Maxwell environment. Given the importance of grounding resistance to ensuring the proper functioning of all electrical systems and even more so for people's safety, it is nevertheless advisable to verify and validate this method for its application during the design stage. The validation of the model has been carried out through the hemispheric electrode, whose mathematical expression for the grounding resistance is well known. However, for other type of electrodes, as grounding rods, the equations usually adopted to design grounding systems provide only approximated values for their grounding resistance. Besides, these equations are able to estimate the grounding resistance only for homogeneous resistivity of the earth. Consequently, traditional methods can give values for the grounding resistance that can differ from the actual behavior due to these uncertainties. In this paper, the use of finite element analysis has been investigated to determine a better estimation of the grounding resistance in different scenarios and to find the distribution of the grounding potential for step and touch voltages calculation on particular critical conditions.

Index Terms—FEM analysis; grounding system; step and touch voltages

I. INTRODUCTION

Electrical earthing has a great importance in transmission, distribution and application of the electrical energy. Indeed, it is vital for the safety of users and operators, for the protection of the systems as well as for the correct operation of sensitive electronic and communication devices such as PLCs and AC drives [1, 2]. Therefore, it must then be suitably designed and sized to perform these important functions [3]. The traditional employed methods for calculating the grounding resistance of rods, meshes, loop or of their combinations, are based on simplified formulas that use charts and graphs that cannot provide precisely the value of the arrangement or the behavior of the ground [4 - 6].

This work proposes a computational method based on the principles of electromagnetism implemented in the finite element (FEM) analysis software Ansys Maxwell to calculate the grounding resistance considering different scenarios. The paper is structured as follows: in Section 2 a brief description of the theoretical aspects of the grounding system considering the hemispheric electrode and meshed system is reported. Section 3 highlights the FEM analysis and discusses the results of the comparison between simulations and approximated standard equations. Section 4 provides two particular case studies, the first one is focused on a non-uniform resistivity of the earth, while the second one pays its attention on partial underground metal bodies close to a mesh grounding system. The authors' conclusions follow in Section 5.

II. THEORETICAL ASPECTS OF THE GROUNDING SYSTEM

To validate the FEM model, first it has been considered a hemispheric electrode, sufficiently distant from the return electrode in order to consider radial the current field. Each hemispherical ground layer, during the flow of the current, has the infinitesimal resistance indicated in (1):

$$dR = \frac{\rho dr}{2\pi r^2}$$

where $\rho$ represents the ground resistivity and $r$ is the distance from the center. Figure 1 shows the hemispherical electrode with the geometrical quantities.

![Figure 1. Representation of the hemispheric electrode.](image)
of a hemispherical electrode can be calculated as the sum of all elementary contributions, as shown in (2).

\[ R_e = \int_{r_0}^{r} \frac{\rho \, dr}{2\pi r^2} = \frac{\rho}{2\pi r_0^2} \]  

(2)

At a certain distance from the electrode, the section of the ground involved by the current flow is so high that the resistance is almost null [7 - 9]. However, in proximity of the electrode, the sections crossed by the current are narrowed and the resistance offered by the ground increases. In particular, one half of the ground resistance is concentrated between the radius \( r_0 \) of the hemispheric electrode and twice the same radius as shown in (3):

\[ R_e = \int_{r_0}^{2r_0} \frac{\rho \, dr}{2\pi r^2} = \frac{\rho}{2\pi} \left( \frac{1}{r_0} - \frac{1}{2r_0} \right) \]  

(3)

The hemispheric electrode, although it is not really used, has great importance in the study of grounding systems since equipotential surfaces of any grounding rods become hemispheric at a sufficiently long distance form the rods themselves. Therefore, it is possible to approximate any shaped rod with a hemispherical electrode having an equivalent radius as reported in (4):

\[ r_e = \frac{\rho}{2\pi R_e} \]  

(4)

Another aspect that has been examined is distribution of the earth potential above a ground mesh, buried one meter in the ground, that disperses a current \( I = 10 \) A. The results from the FEM analysis will be compared with the standard relation used to design ground mesh integrated with vertical rods, as reported in (5):

\[ R = \frac{\rho}{4\pi r} + \frac{\rho}{L} \]  

(5)

where \( \rho \) represents the ground resistivity, \( r \) is the radius of the equivalent circle that has the same area of the mesh and \( L \) is the total length of the vertical rods.

III. FEM MODELING: RESULTS AND DISCUSSION

The mathematical analysis above described has been used to validate the FEM model of the different grounding systems that are under investigation [10 - 12]. The first model that has been implemented consists of a hemispheric electrode of 1 m radius with a constant resistivity of the ground that surrounds the electrode itself and varied in the different simulations from 100 \( \Omega \)m up to a value of 500 \( \Omega \)m. The ground was modeled as a cylinder with a height and radius equal to 3 km. These values have been chosen much larger than the size of the rod in order to be sure that the potential is substantially null at the external border and so to avoid edge effects. In all simulations, a 10 A current has been injected into the ground rod in order to evaluate the potential on the surface from the rod itself to a sufficient long distance characterized by a null the ground potential.

A. Step and touch voltage

Step potential is the step voltage between the feet of a person standing near a grounded object became live after a fault. Figure 2 shows how a person can be subject to step or touch voltage.

B. Hemispheric electrode

By performing a simple relationship between the potential difference, across the surface of the conductor and the infinite distance point, and the injected current it is possible to calculate the ground resistance \( R_e \) which is then compared to that obtained by the theoretical formulas. Figure 3 confirms what it was predicted by theoretical analysis, i.e. the equipotential surfaces are hemispheric and centered with the electrode itself.

The results obtained using Ansys Maxwell point out that soil resistance is inversely proportional to the radius of the electrode and directly proportional to soil resistivity. In addition, comparing the results from FEM analysis with those obtained from the mathematical relation (2), it can be seen that the values for the earth resistance \( R_e \) are almost identical, so that the FEM model can be considered validated.

Figure 4 shows the results for the ground resistance \( R_e \) obtained from FEM analysis and from the exact theoretical relation (2). It is possible to note a good correspondence between them. The equations of the trend lines obtained from software and standard values are respectively \( R_e = 32.389 \, r_0^{-1} \) and \( R_e = 31.832 \, r_0^{-1} \), while the correlation coefficients \( R^2 \) are equal to 0.809 and 0.813.
It has also been verified that half of the grounding resistance is concentrated in the range \((r_0, 2r_0)\) of the hemispheric electrode. Therefore, in the event that a suitable ground resistance cannot be obtained due to the high resistivity of the ground, it is possible to decrease the value of \(R_e\) by replacing part of the soil only close to the electrode with a material characterized by lower resistivity.

C. Ground mesh

The same procedure has been applied to a ground mesh in different configurations, obtaining the results reported in Table I. It is possible to observe that approximated standard formula, e.g. (5), tends to overestimate the value of the earth resistance \(R_e\) increasing the safety margin.

<table>
<thead>
<tr>
<th>Mesh [m²]</th>
<th>Resistivity [Ωm]</th>
<th>Depth [m]</th>
<th>Spacing [m²]</th>
<th>(R_{FEM}) [Ω]</th>
<th>(R_{STD}) [Ω]</th>
</tr>
</thead>
<tbody>
<tr>
<td>50x50</td>
<td>500</td>
<td>1</td>
<td>2.5x2.5</td>
<td>2.99</td>
<td>4.67</td>
</tr>
<tr>
<td>50x50</td>
<td>500</td>
<td>5</td>
<td>5x5</td>
<td>3.89</td>
<td>4.89</td>
</tr>
<tr>
<td>50x50</td>
<td>500</td>
<td>10</td>
<td>10x10</td>
<td>4.07</td>
<td>5.26</td>
</tr>
<tr>
<td>48x48</td>
<td>500</td>
<td>12</td>
<td>12x12</td>
<td>4.60</td>
<td>5.92</td>
</tr>
<tr>
<td>50x50</td>
<td>500</td>
<td>25</td>
<td>25x25</td>
<td>4.68</td>
<td>6.10</td>
</tr>
</tbody>
</table>

To reduce the ground resistance it is preferred to increase the total surface of the mesh, rather than reduce the spacing. In Figure 5, it is possible to see the results of simulations from a graphical point of view, in particular the uniformity of the earth potential as a function of the spacing.

The performance of a ground mesh has been evaluated considering the potential distribution above and around the mesh itself. Consider the ground mesh of Fig. 6, made with copper conductors of section \(S = 95 \text{ mm}^2\), \(L = 50 \text{ m}\) and spaced at 10 m.

Figure 7 shows, as a function of the distance \(d\) from the center of the mesh, the potential distribution on the surface of the ground along the directions A-A’, B-B’ and along the diagonal C-C’, assuming that the mesh is 1 m buried, the ground is homogeneous with resistivity \(\rho\) equal to 500 Ωm and the dispersed current \(I\) is equal to 10 A.

As found from FEM analysis, within the electrode area and along the three directions considered, the potential on the ground surface oscillates in a short range keeping low both step and touch voltages. Instead, on the edge of the mesh, step and touch voltages can assume dangerous values due to the sudden variation of the ground potential. It is also possible to observe that along the diagonal C-C’ the potential distribution on the surface has a greater unevenness so that in this direction there are the greater step and touch voltages. Considering the same area of the mesh, the potential distribution on the surface is as uniform as the spacing is thick, thus giving rise to smaller values of step and touch voltages. Figure 8 shows, for three different mesh spacing, the potential distribution on the surface along the semi-diagonal O-C’. It is possible to note that the lower spaced mesh (5x5 m²) has greater and more uniform potential compared with the other two, so both step and touch voltages are lower.

Instead, on the edge of the mesh the behavior is substantially independent from the spacing, so a ground mesh electrode or a ground ring electrode have the same potential distribution outside the protected area.
In order to limit the step and touch voltages along the edge, an uneven spaced mesh can be realized, thicker toward the border and less dense inside, in order to level the potential distribution on the surface. Even if this solution can be attractive to reduce the cost of the grounding system, from Fig. 9 it is possible to observe that thicker spacing on the edge does not produce any improvement for the step and touch voltages on the border. The same result is presented in graphical way in Fig. 10.

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IV. PARTICULAR STUDY CASES

A. Effect of partially buried metal bodies close to the ground mesh

This section deals with the effect of a partially buried metal body close to the ground mesh. This is a typical case of street poles lighting or protective guard-rail close to a primary HV/MV substation. Indeed, these metallic parts can be touched even if they can assume a dangerous potential in case of line-to-ground fault inside the substation. In this situation, the direct connection of the external metallic parts with the mesh produce dangerous conditions, since a high potential is transferred outside the equipotential area. Two simulations have been performed using a 50x50 m² ground mesh 1 m buried and 10x10 m² spaced. Moreover, a 20 kA ground current has been assumed as a typical value of the line-to-ground fault for a HV system. In the first case, the metallic part, constituted by a cylindrical pole, is not connected to the ground mesh, while in the second simulation a direct connection has been made through an equipotential conductor. In either cases, the metallic part has been located close to the vertices of the ground mesh where the voltage derivative assumes its higher values. This can be considered the worst case for step and touch voltage. Fig. 11 show the arrangement of the simulated case.

As it can be seen from the graph of Fig. 12, the touch voltage for a metallic part installed at 1 m from the mesh, and not connected together, reaches its maximum value, around 16 kV, if the feet of a person are positioned about 2.5 m far from the mass. If instead, the person is 4 cm far from the pole, the touch voltage decreases to 380 V.

All the considerations so far presented can be qualitatively made by observing Fig. 13 where it shows the potential difference between the mesh and the metallic part if the latter is directly (a) or not (b) connected to the mesh.
B. Soil with non-uniform resistivity

The second case analyzed considers the unevenness of the resistivity of the soil. Since normally the soil is not homogeneous, its resistivity varies in the various directions. It is, therefore, necessary to analyze how this affects the value of ground resistance [13] in the hypothesis that the resistivity varies with layers of variable thickness.

The representation of the ground through a model with more than two layers certainly returns the most accurate results, but will rarely be economically justifiable and technically possible to model all these resistivity variations of the soil. Simulations were carried out using the Ansys Maxwell software evaluating how ground resistance varies depending on the resistivity of the various soil layers in the case of a 2 m long vertical cylindrical rod with a diameter of 50 mm. The first two simulations (Fig. 14) were carried out by modeling the soil with five layers with a thickness of 30 cm decreasing resistivity starting from 500 Ωm for the upper layer to 100 Ωm for the deepest in the first case, and from 1000 Ωm to 200 Ωm for the second case.

![Figure 14. 2D multi-layer ground representation.](image)

Subsequently, other simulations have been performed in which the thickness of the various layers is varied. It is possible to observe that soil resistance increases as the thickness of the various layers increases. Figure 15 shows how the equipotential surfaces modify changing the thickness of the various layers. In particular, the potential distribution is more concentrated close to the rod in higher resistivity soil, that means an increase on the ground resistance.

![Figure 15. Equipotential lines of 5-layer soil (a) layers of thickness 30 cm and (b) layers of thickness 1 m.](image)

V. CONCLUSIONS

The purpose of this work was to define an alternative method for assessing soil resistance by using FEM methods. This method allows to consider more particular cases than the standards define for the calculation of the earth resistance for different ground electrodes. The model has been validated comparing the well-known equation of the earth resistance for a hemispheric electrode with one simulated using the FEM analysis.

Particular attention has been paid to the analysis of ground meshes, going to study the behavior of the variation in their size and internal spacing. It has been seen how standard equations for the calculation of the ground resistance in these cases are in favor of safety as the obtained values are higher than the actual ones. Further observation can then be made on the use of differentiated meshes with thicker spacing toward the edge that reduce the cost for their installation, keeping the same performances in the equipotential area.

Another important case here analyzed is related to the effects of a partially buried metal body close to the ground mesh. Especially for HV/MV substations, the possibility to transfer dangerous potential outside the equipotential area suggests to avoid the use of metallic parts, as street pole lighting or guard rails, in favor of insulating materials as composite materials.

Another benefit of using FEM analysis is the ability to model the soil with many layers characterize by different resistivity ensuring a more faithful representation of the real behavior of the grounding system. In fact, the resistivity distribution inside the soil can affect the actual value of the ground resistance.

A future development of this work could be the investigation of the frequency variation, in particular the behavior of the soil for high frequency component that characterize power electronic devices or telecommunication systems.

REFERENCES


