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The Influence of Moisture and Temperature on the Behavior of Soil Resistivity in Earthing Design Using Finite Element Method

Sajad Samadinasab*, Farhad Namdari, Mohammad Bakhshipour
Department of Electrical Engineering, Lorestan University,
Daneshgah Street, 71234-98653, Khorramabad, Lorestan, Iran
*Corresponding author, e-mail: sajad.samadinasab@gmail.com

Abstract

Protection of equipment, safety of persons and continuity of power supply are the main objectives of the grounding system. For its accurate design, it is essential to determine the potential distribution on the earth surface and the equivalent resistance of the system. The knowledge of such parameters allows checking the security offered by the grounding system when there is a failure in the power systems. A new method to design an earthing systems using Finite Element Method (FEM) is presented in this article.In this approach, the influence of the moisture and temperature on the behavior of soil resistivity are considered in EARTHING system DESIGN. The earthing system is considered to be a rod electrode and a plate type electrode buried vertically in the ground.The resistance of the system which is a very important factor in the design process is calculated using Finite Element Method. Finite Element Method is used to estimate the solution of the partial differential equation that governs the system behavior. COMSOL Multiphysics 4.4 which is one of the packages that work with the FEM is used as a tool in this design.Finally the values of the resistance obtained by COMSOL Multiphysics are compared with the proven analytical formula values for the ground resistance, in order to prove the work done with COMSOL Multiphysics.

***Keywords**: Finite Element Method (FEM), earthing design, grounding grids, soil resistivity, soil moisture, soil Temperature*

1. Introduction

Grounding grids are, without doubt, the most important part of an electrical system from the point of view of the safety of people and equipment. The safety, reliability, and correct operation of electrical power systems depend on the quality of the design and construction of their grounding grids [1]. Earthing is the art of making a connection to earth in order to protect the power system's equipments and the personnel who work in it from the danger of electrical shocks. A complete grounding system might include only one earth electrode, an entire group of electrodes with a grounding grid, or anything in between and beyond. In many of the applications of grounding, low grounding resistance is essential to meet electrical safety standards [2]. The ground resistance for a given fault current determines what hazardous voltages exist inside or around the substation or generating station. Consequently, the ground resistance is an important technical parameter which is related to the safety of people and equipment. If the ground resistance is too high and an earth fault occurs, personnel may be killed or injured and equipment may be damaged [3]. The earth must be treated as a semiconductor, while the grounding electrode itself is a pure conductor. Knowledge of the local soil conditions is mandatory and is the first step in the design process. An Accurate design of a grounding system requires an accurate assessment of the site's soil conditions. These factors make the design of a grounding system complex [4].

One important step in designing a grounding system is to estimate the ground resistance of the grounding grid. The different calculating methods the ground resistance of the grounding grids are based on the determination of grid voltage or grid capacitance. The first method is based on determining the grounding grid potential, usually by means of the image method [5]. The second method is based on determining the electrode capacitance on the basis of the relation between electric charge and potential, once the electric field in the soil has been

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calculated. Once were obtained the grounding grid potential and the earth fault current, the ground resistance of the grounding grid is calculated by applying Ohm's law. Simple formulas for calculating ground resistance in square grounding grids have been proposed by Dwight et al. [6–9], in rectangular grids by Schwarz [10], and in grounding grids of any shape by Thapar et al. [11]. Current grounding grid calculation methods determine ground resistance and the step and touch voltages using different mathematical techniques. These techniques are use of the hypotheses that allow us to model the real system in theoretical systems with comparable results. These studies are performed generally for symmetrical grounding grids with uniform, two-layer, or multilayer soils [12–15].

Recently, studies based on the finite-element method (FEM) have been used to calculate ground resistance of grounding grids. The FEM allows obtaining the grounding resistance as a function of the resistivity of soil. Then, it will be possible to justify the use of finite element method in dimensioning of the grounding systems. The first simulation studies of grounding grid behavior using the FEM were based on calculating ground resistance for an arbitrary grid potential (once the grid current is known). The grid current for the grid potential set is determined by means of a current flow analysis. Once the current is calculated, ground resistance is determined as the quotient between the voltage set and the current calculated [1]. Model size selection was difficult in this method, and this conditioned the value of the calculated ground resistance. To decrease the error of the ground resistance calculated, electrical power engineers were forced to analyze models of different sizes with a high number of nodes. Due to the low levels of accuracy of the results and the long calculation times required, this method is not very feasible. As a result of the difficulties of the method outlined above, a new method to design an earthing systems using Finite Element Method (FEM) is presented in this paper. In this method, from the finite element method is used to estimate the solution of the partial differential equation that governs the system behavior. In proposed method, the influence of the moisture and temperature on the behavior of soil resistivity is considered in earthing system design. The earthing system is considered to be a rod electrode and a plate type electrode buried vertically in the ground. Also the ground resistance to be determined by using the finite element method and with calculate the dissipated power or from the stored energy. Then with integration of the surface density is calculated the size of the current passing through of the grounded rod or region. Finally, the ground resistance is determined as the quotient between the voltage and the current calculated. This method has the additional advantage of being independent of the boundary condition, shape, and size of the grid and soil structure. The method presented in this paper proves highly useful in determining precise formulas for calculating ground resistance in different kinds of grounding grid, with no need to build and measure large numbers of grounding grids or study scale models.

2. Earthing Systems

Earthing or grounding may be described as system of electrical connection to the general mass of earth. This system of electrical connection consists of components of an electrical system and metal works associated with equipment, apparatus and appliances. This system provides protection to personnel, equipment and buildings.

2.1. Requirement of Earthing Systems Design

A good grounding system -also known as an earth electrode system -is important for the protection of an overall system facility. Therefore, a safe grounding grid design has the following main objectives [1]:

- To protect personnel against electrical risks by limiting the touches and step voltages to safe value, for assuring that if ground faults occur in substations or generating stations, a person in the vicinity of grounded facilities is not exposed to the danger of critical electric shock;
- Electromagnetic compatibility (EMC), limitation of electromagnetic disturbances of the electricity supply network and to ensure safety, good power quality and continuity of electrical equipment by limiting the over voltages that can appear under extreme operation conditions or in case of an accident;

- to ensure correct operation of equipment and electrical protection devices by enabling ground faults to be detected and actions selected to disconnect those zones of the electrical installation where faults occur;
- To provide means to carry electric currents into the earth under normal and fault conditions, without exceeding any operating and equipment limits.
- Provide protection of building and insulation against lightning.

2.2. Components and Parameters of Earthing Systems Design

The main Components of a safe grounding grid design are [16]:

- Earth: The location to be grounded must first be analyzed to determine the soil structure, type, depth and resistivity of each layer of the soil, and to have a background investigation of any buried cables, metallic pipes, etc.
- Earth electrode: a metal conductor or a system of interconnected metal conductors, or other metal parts acting in the same manner embedded in the ground and electrically connected to it.
- Earth resistivity (ρ): the resistance measured between two opposite faces of a one meter cube of earth which is expressed in unit of Ω.m. Soil resistivity is the key factor that determines what the resistance of the charging electrode will be and to what depth it must be driven to obtain low ground resistance. The resistivity of soil varies widely throughout the world and changes seasonally. The lower the resistivity the fewer the electrodes required to achieve the desired earth resistance value. It is an advantage to know the resistivity value at the planning stage as it gives an indication for how much electrode is likely to be required. Usually there are several soil layers each having different resistivity in which case the soil is said to be non-uniform. Thus, uniform soil is the soil that has one layer with constant value of resistivity. Measurements help define the layers of the soil and they show that the resistivity is a function of the depth [16].
- Earthing resistance: Since soil exhibits a resistance to the flow of an electrical current and is not an “ideal” conductor, there will always be some resistance (can never be zero) between the earth electrode and “true Earth”. The resistance between the earth electrode and “true Earth” is known as the Earth Resistance of an electrode, and it will depend on the soil resistivity, the type and size of the electrode and the depth to which it is buried.

Table 1 shows the values of the resistivity for various types of soil [5].

Table 1. Example of resistivity value for various soil types

Type of ground	Ground resistivity ρ [Ω.m]	
	Range of values	Average values
Boggy ground	2-50	30
Adobe Clay	2-200	40
Slit and sand-clay ground, humus	20-260	100
Sand and sandy ground	50-3000	200 (moist)
Peat	>1200	200
Gravel (moist)	50-3000	1000 (moist)
Stony, and rocky ground	100-8000	2000
Concrete: 1 part cement+3 parts sand	50-300	150
1 part cement+5 parts gravel	100-8000	400

3. Finite Element Method

In mathematics finite element method (FEM) is a numerical technique for finding approximate solutions to boundary value problems. This method is similar to the idea that connecting many tiny straight lines can approximate a larger circle. FEM encompasses all the methods for connecting many simple element equations over many small Subdomain, named finite elements, to approximate a more complex equation over a larger domain [17]. In general, the FEM consist of three main matrices, which are: the property matrix, the behavior matrix and the action matrix.

$$\{K\}.\{u\} = \{F\} \tag{1}$$

Where: {K} is the property matrix, {u} is the behavior matrix and {F} is the action matrix. In electrical applications, {K} can represent the dielectric permittivity, {u} can represent the electrical potential and {F} can represent the electrical charge [18].

$$\{u\} = \{F\}\{K\}^{-1} \quad (2)$$

FEM is used to study the behavior of many electrical systems, by finding the solution of the upper equation.

3.1. Laplace's Equation

For steady direct current, the differential relation is defined as follows [19]:

$$\nabla . J = 0 \quad (3)$$

Where: J is the current density. Ohm's Law at a point is:

$$J = \sigma E \quad (4)$$

Where: E is the electric field and σ is the electrical conductivity of the media or material. The electric field E can be obtained as the negative gradient of the electric potential:

$$E = -\nabla . V \quad (5)$$

Where: V is the electric potential. From Equations (3) and (5), the following equations are obtained:

$$\sigma \nabla . V = E \quad (6)$$

$$\sigma \nabla . (\nabla . V) = 0 \quad (7)$$

Finally, the Laplace equation is obtained as follows:

$$V^2 V = 0 \quad (8)$$

To determine specific distribution of the electric field, i.e., to determine uniquely the solution of the differential equation, the boundary conditions given at the boundary of the research region are needed. There are two kinds of boundary conditions:

- Boundary which is far away from the current source, introduces Dirichlet boundary condition [20]:

$$V = 0 \quad (9)$$

Or

$$V = V_0 \quad (10)$$

Where: V is the electric potential and V_0 is a known value.

- Insulating surface (i.e., ground), which is Neumann boundary condition [20]:

$$\partial V / \partial n = 0 \quad (11)$$

Where: n is the normal vector to the boundary.

3.2. Finite Element Grounding Methods

The Most recent studies about grounding analysis are based on Finite Element Methods (FEM). FEM used to determine grounding resistance of a design or a grounded region.

They give more accurate results compared to conventional grounding methods [21]. Old FEM methods are composed of current flow analysis by using electrode potential. After the current is computed, ground resistance can be found by dividing voltage by current. In this method, main disadvantage is selecting the size of the model such as earth distance to be considered is starting from the grounding electrode. Since analysis of each potential in the soil for a selected point is considered from grounding electrode to the point.

New FEM methods are developed by researchers, such as main disadvantage of old FEM method is overcome. In the first step, they assume that grounding resistance is such a parameter that does not depend on potential or current in the electrode. Second assumption is that, the region is an infinite flat surface. Model structure for this solution is given in Figure 1.

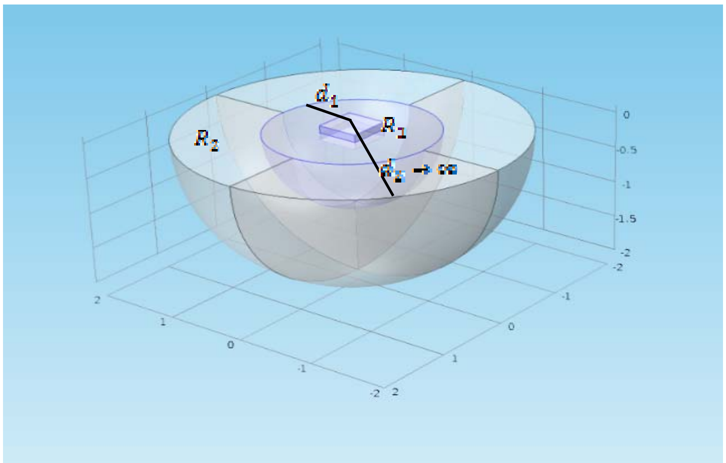

Figure 1. New finite element model of soil

Where: d_1 is the distance from electrode to the points where semi-spherical model of equipotent surface disturb. d_2 is the distance from electrode to the points where electrical potential goes to zero. Technically, this point is at infinity. R_1 is the resistance inside the semi-spherical surface and R_2 is the resistance outside the semi-spherical surface.

From tests of various designs, d_1 can be determined by:

$$d_1 = \frac{D}{2} + 30 \tag{12}$$

Where: D is the diagonal distance of grounding electrode. Resistance of grounding electrode can be derived from Figure 1:

$$R = R_1 + R_2 \tag{13}$$

R_2 is computed from the following equation:

$$R_2 = \frac{\rho}{2\pi d_1} \tag{14}$$

Where: ρ s the soil resistivity. Determination of R_1, is not as simple as R_2. This is where finite element analysis exactly takes its place. In general, R_1 can be calculated from dissipated power given in the following equation:

$$R_1 = \frac{(voltage)^2}{\text{disspeated power}} \tag{15}$$

R_1 can be detailed by replacing the terms as in Equation (15) [1]:

$$R_1 = \frac{(V_G - V_B)^2}{\int_V \sigma E^2 \, dV} \tag{16}$$

Where: V_G is the potential in the grounding electrode, V_B is the potential in the boundary d1, E is the electric field, d_V is the volume element and σ is the electrical conductivity. In this new method, which has been developed, the enables ground resistance to be determined starting from the dissipated power, or from the stored energy (by the electric field) in the model [1].

4. New FEM Method for the Earthing System Design

In this section, the Earthing system design and implementation will be presented. The design has been divided into two parts: the electrode design and the soil design. Each of these parts has its own design criteria, parameters, and constraints. The Design and Implementation was made using a special FEM software package named as COMSOL Multiphysics 4.4, provided with built-in drawing toolbox to help the designer to draw the simulated model with true scales. A two and three dimensional field computer program (COMSOL Multiphysics 4.4) can be used to solve FEM problems. It provides automatic mesh generation for solving electrostatic and electromagnetic problems, by differential operator Finite Element Method. It is also provided with powerful postprocessor techniques to help the designer to analyze the results, make comparisons and even changes in the design which are made very quickly and easily.

When solving the PDEs, COMSOL Multiphysics uses the proven finite element method (FEM). This software runs the finite element analysis together with adaptive meshing and error control using a variety of numerical solvers. The Designing plan starts with determining the Space Dimension, which is a 3D Space, then determining the rod radius, the rod length, the soil radius and the soil length. This idea is to design a model that simulates any desired type of grounding systems such as a vertical grounding rod, a horizontal grounding rod, a plate type electrode or a hemispherical electrode type, driven into the soil, to analyze the voltage gradient around it and on the surface of the soil. Also to calculate the resistance of the entire model consisting of the electrode, the soil and the contact resistance between the electrode and the soil is used of the FEM concept. The design made simulates a vertical grounding rod and a plate type electrode driven into a volume of uniform soil with constant resistivity. The initial model was designed using the basic concepts as in [1] and [17] which will be discussed in the following.

4.1. The concept of Sphere of Influence

Determining how efficiently grounding electrodes discharge electrons into the earth an important concept is the “sphere of influence”. The sphere of influence is the volume of soil throughout which the electrode discharges current into the soil. The greater the volume compared with the volume of the electrode, the more efficient is the electrode. Long electrodes, such as grounding rods, are the most efficient. The surface area of the electrode determines the capacity of the device, but does not affect “the sphere of influence”. The greater the surface area is, the greater the contact with the soil and the more electrical energy that can be discharged per unit of time [16]. Thus the sphere of influence can be taken to be greater than 1.1 times the rod length, in this area no other rods must exist, to avoid interference between sphere of influence of each rod, and to have the maximum efficiency of the grounding system. Figure 2 shows the sphere of influence for a vertical grounding rod.

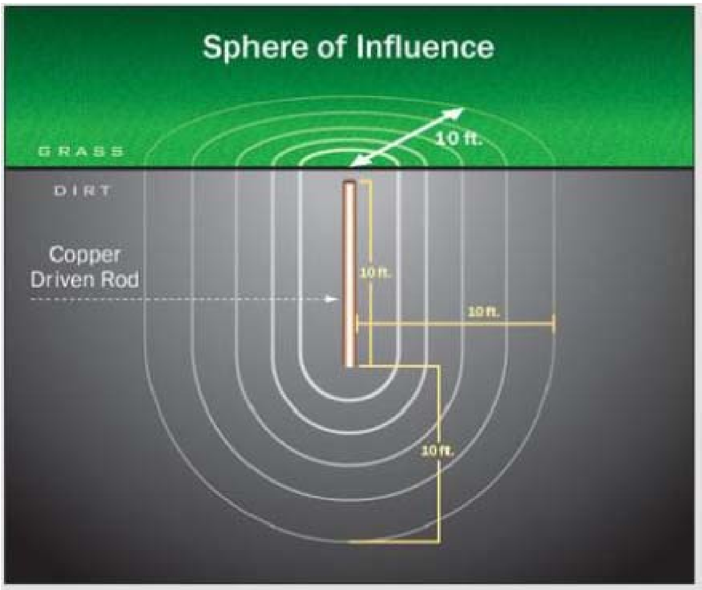

Figure 2. The sphere of influence

4.2. The Grounding Rod Design

The rod, is designed as a cylindrical shaped element with radius r_r, and length l_r, and made of copper with conductivity of copper that is $\sigma_r = 5.99\times10^{7}(\Omega.m)^{-1}$ or resistivity of copper which is $\rho_r = 1.66\times10^{-8}\Omega.m$. The rod is driven vertically into the soil. Considering a rod electrode of a diameter d and length L as shown in figure 2, with the assumptions that the current flow outwards from the vertical section is horizontal and from the lower hemisphere end is radial outwards. The rod resistance is given in [16] as follows:

$$\mathrm{R} = \frac{\rho}{2\,\pi\,\mathrm{L}}[\ln\frac{8L}{d} - 1] \tag{17}$$

Where: L is the buried length of the electrode (m), d is the diameter of the buried electrode (m), ρ is the soil resistivity (Ω.m) and R is the electrode resistance (Ω).

4.3. The Grounding Soil Design

The soil in grounding systems is thought to be as a conductive medium. The soil in the designed model is assumed to be uniform having a constant resistivity ρ_s, or a constant conductivity σ_s. The soil is designed as a cylindrical element surrounding the grounding rod having a radius r_s, and a length or height l_s, with the rod driven vertically into the center of the soil.

This model was designed using the basic concepts as in [1] and [16]. The soil radius is taken to be 2.5 times the rod length to obtain sufficient volume of the soil that guarantees effective current discharge. The rod lengths and radiuses designed were 1m, 2m, 3m, and 0.025m, 0.008m respectively. Table 2 shows the soil radius for the various lengths of rod.

Table 2. Soil radius for each value of rod length

Rod length (m)	Soil radius (m)
1	2.5
2	5
3	7.6

In the proposed method, the soil around the rod is divided into three cylindrical shaped parts, as is shown in Figure 3. The first cylinder which is called the soil grounding system is taken to be with a radius 2.5 times the rod length to obtain sufficient volume of the soil that guarantees effective current discharge. The second cylinder is called the effective soil, usually is considered with a radius and a height of 10 m. The next layer or third cylinder, with a height and radius of more than 10 meters, which does not have significant effect on the soil resistivity are assumed as infinite.

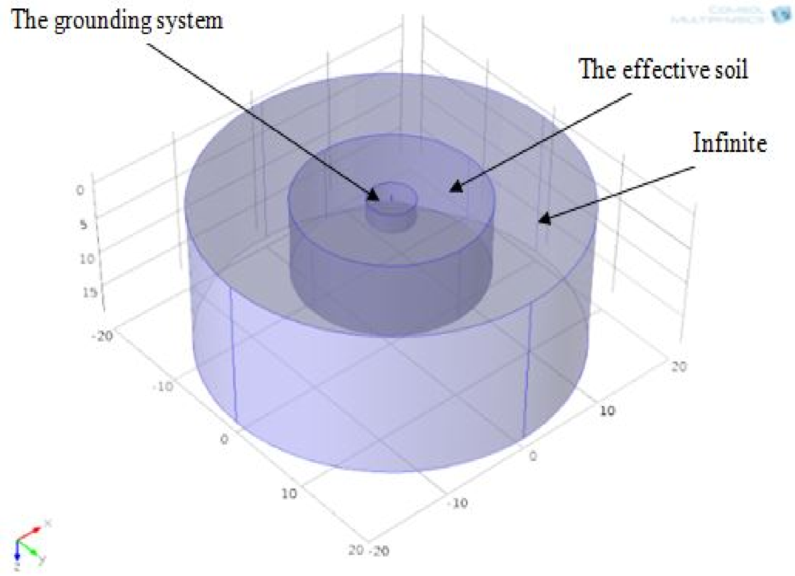

Figure 3. The proposed Earthing design

Tables 3 and 4 are shows soil resistivity changes as functions of soil temperature and soil moisture content, respectively.

Table 3. Soil resistivity changes as a function of soil temperature

Temperature °C	Temperature °F	Resistivity (Ω.m)
20	68	7.2
10	50	9.9
0 (water)	32 (water)	13.8
0 (ice)	32 (ice)	30
-5	23	79
-15	14	330

Table 4. Soil resistivity changes as a function of soil moisture

Moisture Content (% by weight)	Resistivity (Ω.m)	
	Top Soil	Sandy Loam
0	$>1000\times10^6$	$>1000\times10^6$
2.5	250	150
5	165	43
10	53	18.5
15	19	10.5
20	12	6.3
30	6.4	4.2

4.4. COMSOL Multiphysics 4.4 Boundary Settings

Boundary conditions define the interface between the model geometry and its surroundings. Interface conditions on interior boundaries in model geometry can also be set. Also different boundary conditions can be set for each boundary. For the rod, the electric potential boundary is set on V0 =100 volts. For the soil, the boundaries are selected as follows:

- From Conditions Shown in figure 3, the four sides, and the bottom of the soil cylinder were set to Ground Boundary condition.
- The top of the soil cylinder was set to Electrical Insulation Boundary.

Now the model is completely designed as required, all the Subdomain were defined along with the boundary conditions for each boundary of the model.

5. Simulation Results and Discussion

After the model was designed, in order to obtain the solution of the Laplace equation, it must be solved. This model is the model governed by Laplace equation, which is the governing equation for the Earthing system under design. Dependent Variable is by default set to 100 volts, which is the behavior parameter to be studied and analyzed. The Laplace equation is written in the Subdomain Settings dialog box in the Following Form:

$$-\nabla(\sigma \nabla \mathrm{V} - \mathrm{J}^{\mathrm{e}}) = Q_j \tag{18}$$

Where: V is the electrical potential, σ is the electric Conductivity, J^e is the external Current Density and Q_j is the current Source Density.

FEM is known with its unique Triangles. Initialize the Mesh allows the designer to see the triangles made by the COMSOL Multiphysics 4.4 solver, which shown in figure 4.

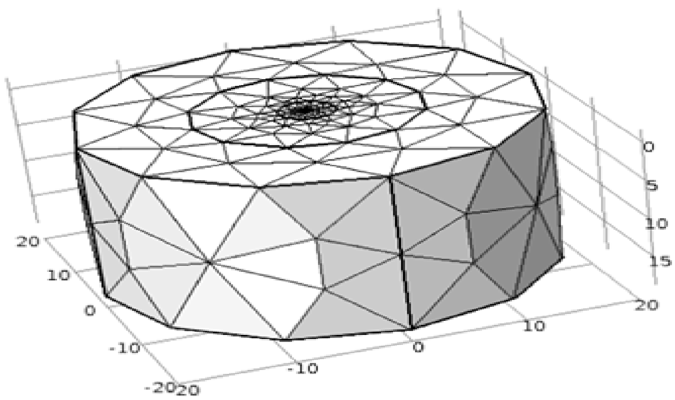

Figure 4. Initialized Mesh Model

The results are obtained by considering effect of temperature and moisture on the resistivity soil. Figure 5 shows the potential distribution on the soil surface and also in a plate surface with a depth of 0.5 m (grounding grid plate). As can be seen the most of the potential distribution is on the surface of the copper plate and whatever becomes farther from the copper plate surface, the potential distribution becomes lower. Figure 6 shows the potential distribution on the soil surface and also in a rod surface with a depth of 1 m. Here also the most of the potential distribution is on the copper rod surface and whatever becomes farther from the copper rod, the potential distribution becomes lower.

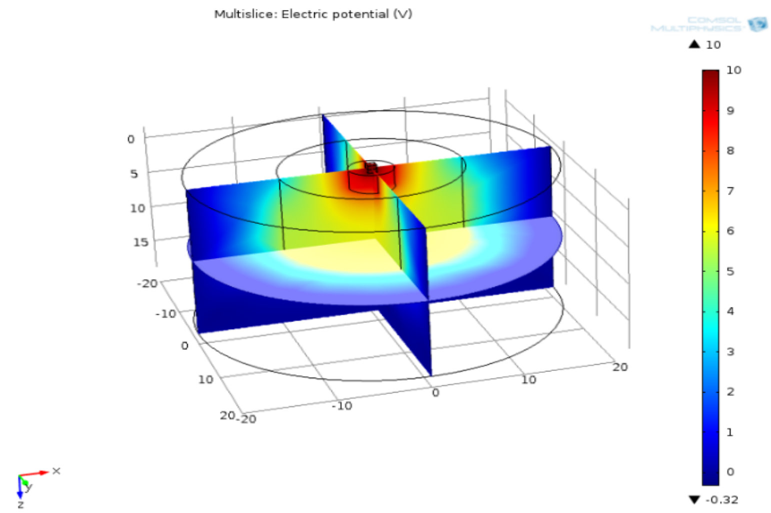

Figure 5. The potential distribution on the soil surface and in a plate with a depth of 0.5 m

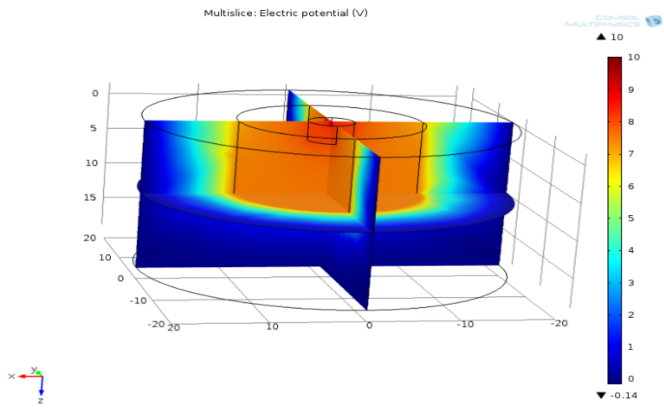

Figure 6. The potential distribution on the soil surface and in a rod surface with a depth of 1 m

Using the equation (15) and with solving the Laplace equation (17), the value of ground resistance of the earthing system for the copper plate is obtained as follows:

$$R = \frac{\text{voltage}^2}{\int_V \sigma \, E^2 \, dV} = \frac{100}{52.7666} = 1.8951\,\Omega$$

Also, the value of ground resistance of the earthing system for the copper rod is obtained as follows:

$$R = \frac{\text{voltage}^2}{\int_V \sigma \, E^2 \, dV} = \frac{100}{29.064} = 3.4407\,\Omega$$

As can be seen, the value of ground resistance for the copper rod is greater from the value of ground resistance for the copper plate. To solve this problem, usually instead of using a single rod, from a network is used which consists of several parallel rods.

Table 5 shows the ground resistance values obtained with the method explained in this paper and those calculated in [1] and [11] using the methods developed by Thapar et al.

Compare the results of design models shows the superiority of the new method presented by FEM.

Table 5. Compare the ground resistance value obtained from the new method with the proposed methods in references [1] and [11]

Method	ground resistance value
the new method presented in this paper	1.8951
Thapar	2.16
Sverak	2.31
Schwarz	2.12
Thapar-Gerez	2.06
the proposed method in reference [1]	2.26

Taking into consideration these results and according to Table 6, we can see that the difference between the values calculated in new method and those proposed in [1] is no more than 18%.

Table 6. The difference between the values calculated with the other references

Method	The difference between resistance value (IN PERCENT)
Thapar	-12.26
Sverak	-17.96
Schwarz	-10.60
Thapar-Gerez	-8.00
the proposed method in reference [1]	-16.14

6. Conclusion

A new method for calculating the ground resistance of grounding grids using the FEM method has been presented in this paper. In this approach the influence of the moisture and temperature on the behavior of soil resistivity are considered in EARTHING system DESIGN. The earthing system is considered to be a rod electrode and a plate type electrode buried vertically in the ground. The numerical value of the resistance of the rod and plate were determined by the finite element method and with calculate the dissipated power or from the stored energy. The Design and Implementation of grounding systems was made using a special FEM software package named as COMSOL Multiphysics 4.4. It provides automatic mesh generation for solving electrostatic and electromagnetic problems, by differential operator Finite Element Method. It is also provided with powerful postprocessor techniques to help the designer to analyze the results, make comparisons and even changes in the design which are made very quickly and easily. This software runs the finite element analysis together with adaptive meshing and error control using a variety of numerical solvers such as PDEs. This idea is to design a model that simulates any desired type of grounding systems such as a vertical grounding rod, a horizontal grounding rod, a plate type electrode or a hemispherical electrode type, driven into the soil, to analyze the voltage gradient around it and on the surface of the soil. Also to calculate the resistance of the entire model consisting of the electrode, the soil and the contact resistance between the electrode and the soil is used of the FEM concept. The design made simulates a vertical grounding rod and a plate type electrode driven into a volume of uniform soil with constant resistivity. The method presented in this paper may be highly useful in determining precise formulae applied to calculating ground resistance in different kinds of grounding grid. Once the ground resistance and the earth fault current are known, the potentials in the nodes of the soil surface and the touch-and-step voltages can be calculated. The results obtained shows the superiority and advantage of FEM analysis method presented in this paper, in comparison with other analytical methods provided for earthing systems design.

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