Advanced Sciences and Technology Journal

ASTJ vol. 1 (2024) 1013
10.21608/astj.2024.342131.1013
https://astj.journals.ekb.eg/

Simulation model for estimating the surface potential resulting from an earthing system using COMSOL Multiphysics

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ARTICLEINFO

Article history:
Received 1 October 2024
Revised 30 October 2024
Accepted 1 December 2024
Available online 5 December 2024

Handling Editor:
Prof. Dr. Mohamed Talaat Moustafa

Keywords:
Earthing system,
Surface potential,
Simulation,
Finite element method,
COMSOL Multiphysics

ABSTRACT

The calculation of the surface potential resulting from the earthing system which is exposed to high voltage is very important due to the required degree of human safety, but this estimation is very complicated so the development of a software program to simulate the surface potential at the ground level is required. A new approach for estimating the surface potential of an earthing system arranged by using driven vertical rods is presented. Where the electric potential distribution is obtained by using Laplace's equation which is calculated by using the finite element method. Three models of different numbers of electrodes buried in homogeneous soil are used; model one is represented by one driven rod, model two is represented by three driven rods that are not connected and arranged in a delta shape and finally, model three is represented by three driven rods that are connected and arranged in a delta shape. The strength of the finite element method in this application is its ability to allow a detailed representation of the types of soils used and different models of the simulation models of the rods. The three different models are used for studying the effect of increasing the number of the driven electrodes of the earthing grid on the value of the surface potential resulting from an earthing system that is exposed to high voltages.

1. Introduction:

Simulation programs are used for solving and modelling the most scientific problems in engineering research. The distribution of the surface potential on the ground surface that resulted from exposing the earthing system to high voltages is considered as one of the most important scientific problems in the electrical engineering power field. This is because of the non-linear relation between different equations and variables which are used for calculating the surface potential.

This problem has been a challenge to all power engineering since the development of industry and the huge amount of electricity used. So, the developments of different simulation methods are investigated to obtain an accurate solution for surface potential distribution [1].

There are different types of earthing systems [2], as one of the simplest means and most used is the vertical ground rods for earth termination to protect the systems from high voltage, high current and lightning protection [3].

The numbers of the vertical rods and their arrangements influenced the surface potential value and distribution. To improve the grid performance the number of vertical rods should be increased to reduce the grid resistance and then the surface potential values will be in the safe ranges for humans [3-6].

Electric field distribution is one of the main factors which are required for calculation of the surface potential for a proper design of an earthing system. For a simple physical system, it is usually possible to find an analytical solution. However, in many cases, the physical systems are so complex that it is extremely difficult, if not impossible, to find analytical solutions [1, 4, 7-11]. Simulation methods are employed for estimating the electric field and the surface potential distribution such as the Charge Simulation Method (CSM) [4, 8, 11, 12], and the Finite Element Method (FEM) [1, 13].

In this paper three models for simulating the electrical surface potential are used. This scientific problem is considered as a three dimensional field problem with different types of earthing grids, these models are built and the materials of the models are selected from the large library of the software program COMSOL Multiphysics [14], parameters of the materials are defined for each model of the three models for different numbers of electrodes that are buried in homogeneous soil; case one is represented by one driven rod, case two is represented by three driven rods not connected together arranged in delta shape and case three is represented by three driven rods connected together arranged in delta shape. The finite element method (FEM) is used for calculating the surface potential and the electric field distribution at the soils surfaces and in the surrounding medium in the region where the earthing system is buried. This is achieved by using COMSOL Multiphysics program.

2. Method of analysis

2.1 Electric field and potential distributions

From the Laplace's equation [15], the divergence of the gradient potential distribution without any surface and space charges density is given by,

$$\nabla^2 \emptyset = 0.0 \qquad (1)$$

where, $\emptyset$ is the potential at any point in the medium given in per unit value ($p.u.$) of the base voltage.

In the Cartesian coordinates system, the three-dimensional functional $F(\emptyset)$ of the integration of Laplacian equation can be formed as follows [16],

$$F(\emptyset) = \frac{1}{3}\int_v \varepsilon \left[\left(\frac{d\emptyset}{dx}\right)^2 + \left(\frac{d\emptyset}{dy}\right)^2 + \left(\frac{d\emptyset}{dz}\right)^2\right] dx\, dy\, dz \quad (2)$$

where, ε is the dielectric constant of the dielectric medium.

After obtaining the surface gradient potential at any point in the medium the electric field intensity E, can be obtained from [15]:

$$E = -\nabla\emptyset \qquad p.u. \qquad (3)$$

Then, at every knot in the total network composed of many triangle elements, the simulation of the surface electric potential was carried out by minimizing the function $F(\emptyset)$,

$$\frac{\partial F(\emptyset_i)}{\partial \emptyset_i} = 0.0 \quad ; i = 1, 2, \ldots, m \qquad (4)$$

where, m is the number of knots in the mesh network.

2.2 Specifying the boundary condition

Numerical calculations were performed using COMSOL Multiphysics [14]. In general, a three-dimensional space problem is divided into triangular elements and the variables are approximated by third order polynomials in each element.

The surface electric potential satisfies Laplace's Equation (1), with the following boundary conditions. On the three surface edge of the cubic domain, see Fig. 1, the normal gradient of the face surface is equal to zero,$\partial\emptyset/\partial \mathrm{n} = 0$, the potential at each vertical rod having a voltage, V, equal to $1\ p.u.$ with boundary equation $\emptyset = V$. Finally, the bulk of the medium satisfy Laplace's equation, $\nabla^2\emptyset = 0.0$.

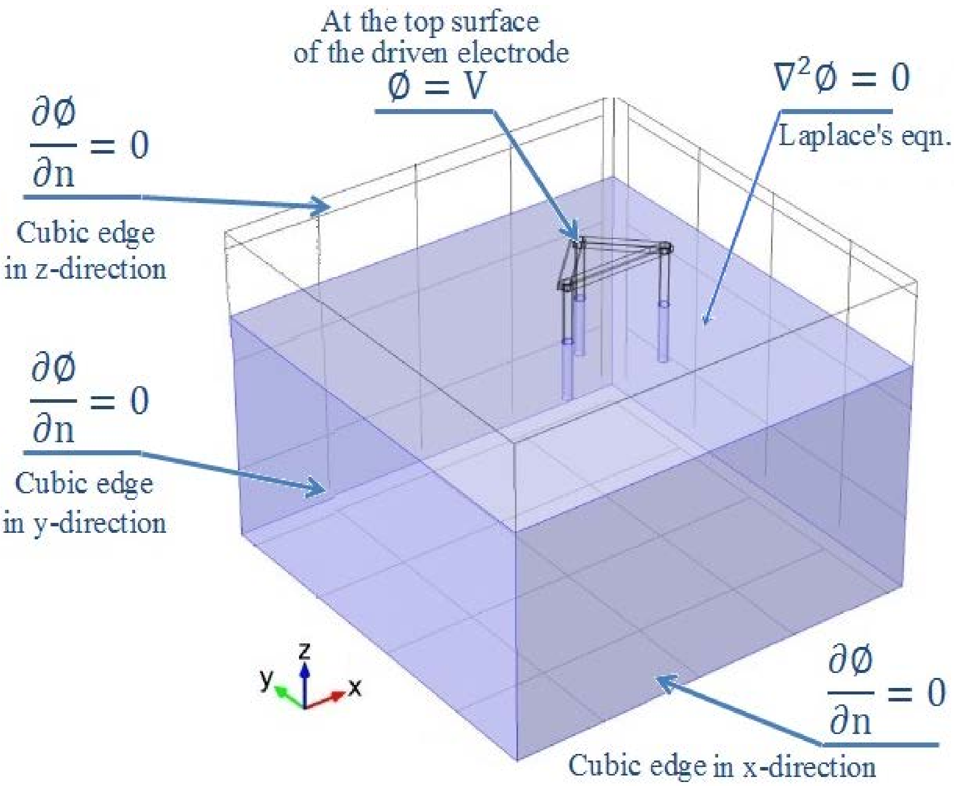

Fig. 1. A schematic diagram of the 3D problem space for numerical solution of the surface electrical potential $\emptyset$.

3. Models Design

This paper presented three different models for studying the characteristics of the earthing system and noticing the improvement in the system performance due to the numbers and the arrangements of the driven rods.

Model 1: One driven vertical rod is buried in homogeneous soil.
Model 2: Three driven vertical rods (not connected) are buried in homogeneous soil.
Model 3: Three driven vertical rods (connected) are buried in homogeneous soil.

The selected material for the driven rod is copper with its predefined properties as cleared in the table of the material parameters used by COMSOL Multiphysics program, in Table 1, the basic property of the material is obtained from COMSOL Multiphysics library.

Table 1: Basic settings of the copper material

Description	**Value**
Relative permittivity	1
Electrical conductivity	5.998E7 [S/m]
Heat capacity at constant pressure	385 [J/(kg*K)]
Density	8700 [kg/m^3]
Thermal conductivity	400 [W/(m*K)]

The selected material for the domain of the cubic sample is Black Pottery Clay [solid and homogeneous] with its predefined properties as cleared in Table 2.

Table 2: Basic property of the clay soil material

Description	**Value**
Relative permittivity	15
Density	rho (T[1/K])[kg/m^3]
Thermal conductivity	k(T[1/K])[W/(m*K)]

Both of rho, "density", and k, "thermal conductivity" are function of Heat capacity at constant pressure, "(T[1/K])", the basic property of material obtained from COMSOL Multiphysics library.

3.1 Model 1: one- driven vertical rod buried in homogeneous soil

Figure 2, shows the geometry of the first model of one driven rod in homogeneous soil, this electrode is made of copper with $2\ m$ in length, $20\ cm$ in diameter, buried in a sample cubic of earth has dimension of $8\ m$ in length, $8\ m$

in width and $5.5\ m$ in height also the distance between the upper surface of the driven rod and the surface of the earth is $0.5\ m$. The rod is subjected to an applied voltage of $V = 1\ p.u.$

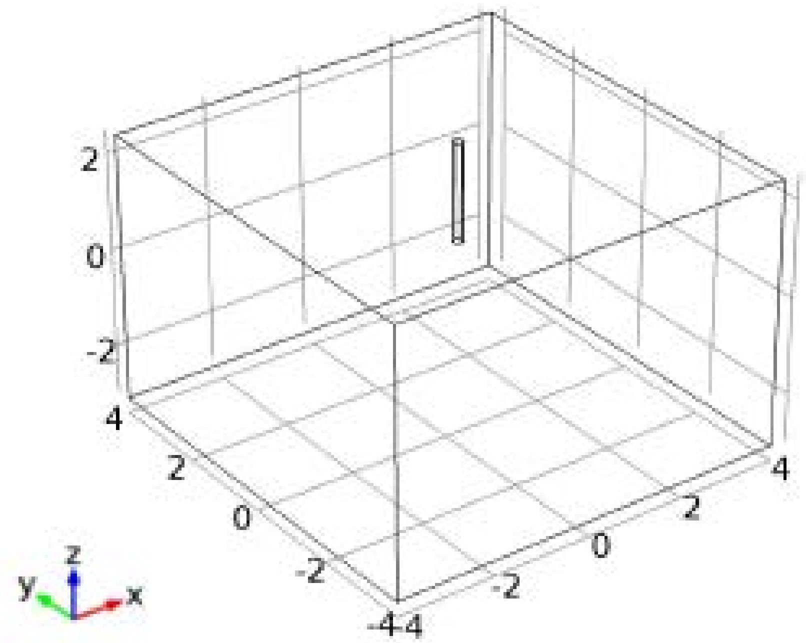

Fig. 2. One vertical rod buried in a homogeneous soil.

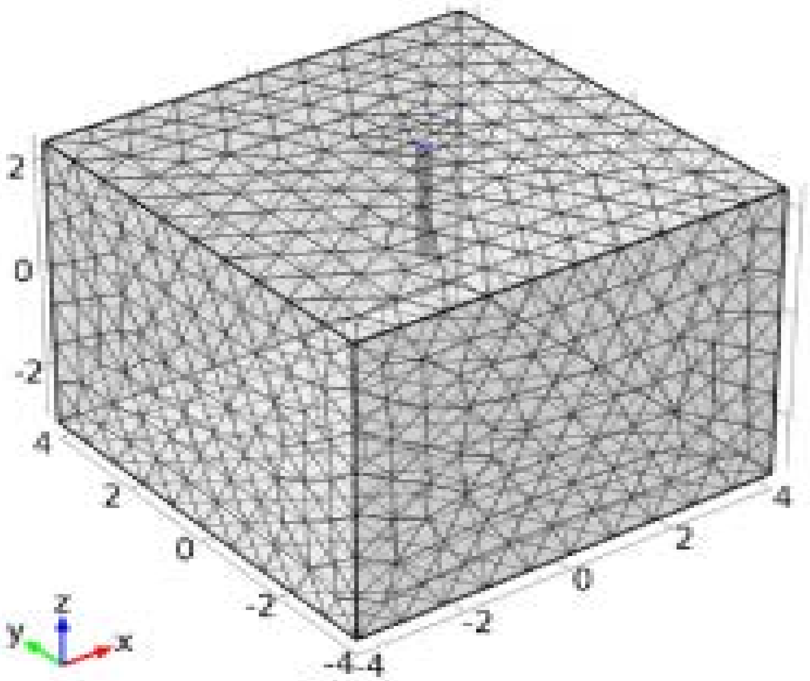

Fig. 3. Mesh analysis of one vertical rod model

3.1.1 Mesh analysis for one vertical rod.

As shown in Fig.3 mesh analysis of the model is done by the program and generates Table 3, that is describing the settings and statics of the mesh.

Table 3: Mesh statics from COMSOL Multiphysics program for one vertical rod.

Statics		**Size Settings**	
Property	**Value**	**Name**	**Value**
Min. element quality	0.2023	Max. element size	0.8
Element quality	0.7377	Min. element size	0.144
Tetrahedral elements	14883	Resolution of curvature	0.6
Triangular elements	1476	Resolution of narrow regions	0.5
Edge elements	176	Max. element growth rate	1.5
Vertex elements	16		

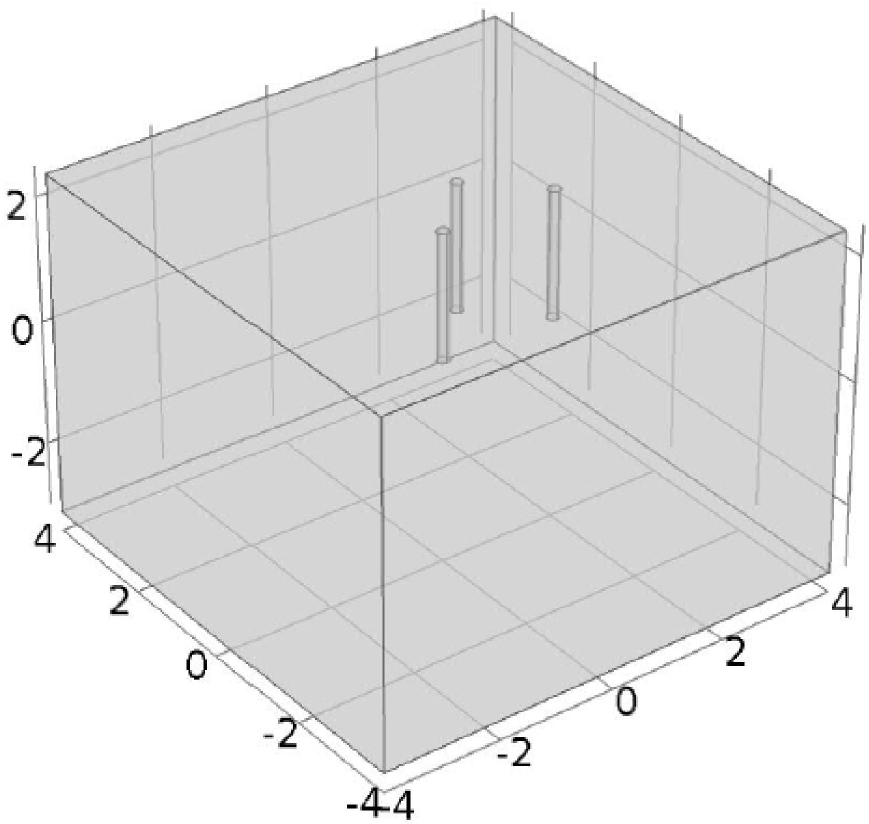

Fig. 4. Three vertical rods not connected and buried in a homogeneous soil.

3.2 Model 2: Three- driven vertical rods (not connected) buried in homogeneous soil

Figure 4, shows the geometry of the second model of the three driven vertical rods of copper in one layers earth model with dimensions of $2\ m$ in length, $10\ cm$ in diameter, $2\ m$ distance apart for each rod from the other one of the three rods forming a positions of triangle shape and buried in sample cubic of earth has dimension of $8\ m$ in length,$8\ m$width and$5.5\ m$ in height also the distance between the top of rods to the surface of the earth is $0.5\ m$.The voltage applied for one rod (energized driven electrode) is$V = 1\ p.u.$

3.2.1 Mesh analysis for three vertical rods not connected.

As shown in Fig.5, mesh analysis of the model is done by the program and generates Table 4 that is describing the settings and statics of the mesh.

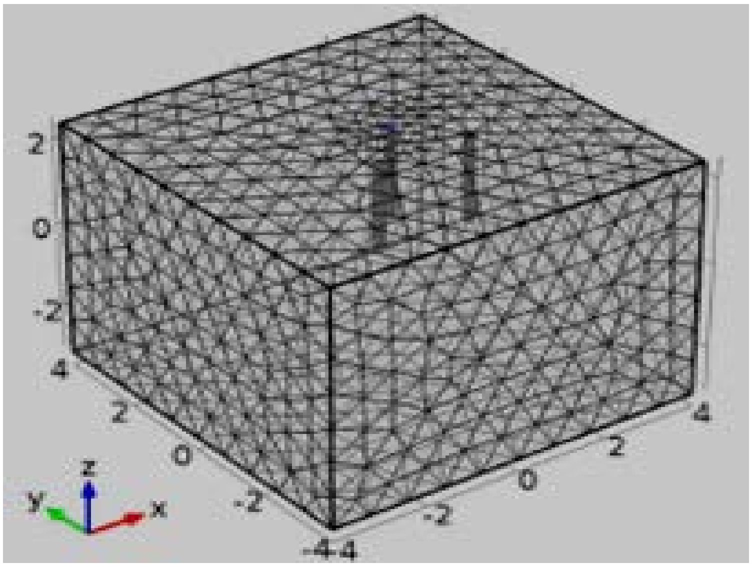

Fig. 5. Mesh analysis of three vertical rods model not connected.

Table 4. Mesh statics from COMSOL Multiphysics program for three vertical rods not connected.

Statics		Size Settings	
Property	**Value**	**Name**	**Value**
Min. element quality	0.06746	Max. element size	0.8
Element quality	0.7129	Min. element size	0.144
Tetrahedral elements	22514	Resolution of curvature	0.6
Triangular elements	1990	Resolution of narrow regions	0.5
Edge elements	312	Max. element growth rate	1.5
Vertex elements	32		

3.3 Model 3: three driven vertical rods (connected) buried in homogeneous soil.

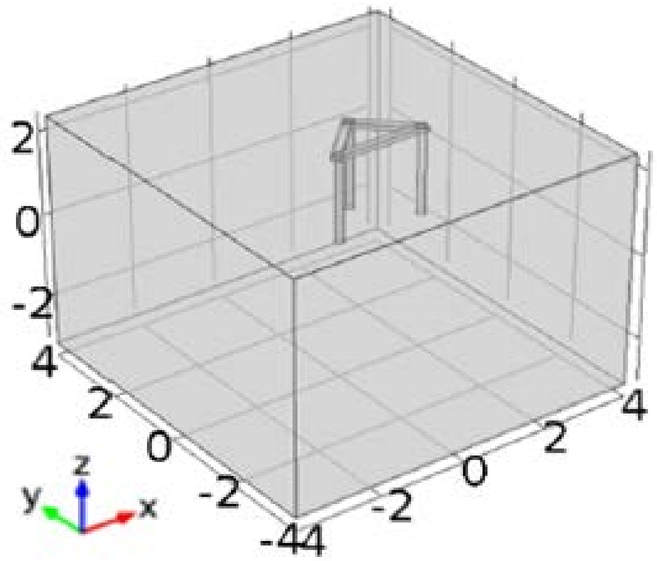

Fig. 6. Three vertical rods connected and buried in a homogeneous soil.

Figure 6 shows that the three driven vertical rods of copper connected in one layer earth model with the same dimensions of model 2 described in section 3.2.

3.3.1 Mesh analysis for three vertical rods connected.

As shown in Fig.7, mesh analysis of the model is done by the program and generates Table 5 that is describing the settings and statics of the mesh.

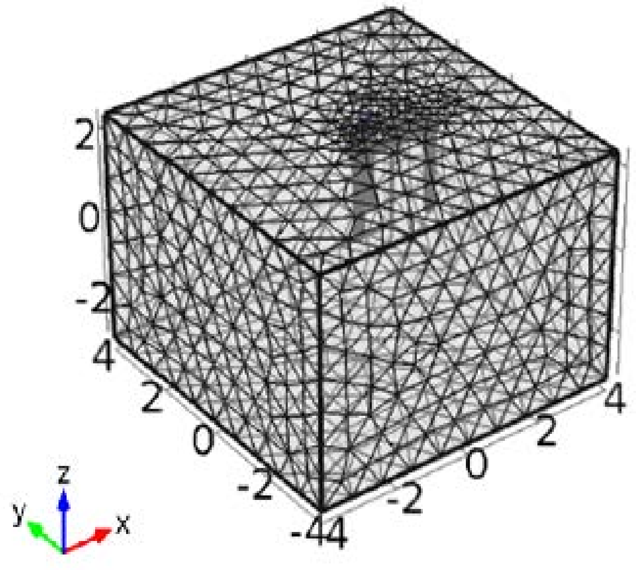

Fig. 7. Mesh analysis of three vertical rods model connected.

Table 5. Mesh statics from COMSOL Multiphysics program for three vertical rods connected.

Statics		Size Settings	
Property	**Value**	**Name**	**Value**
Min. element quality	1.248E7	Max. element size	0.8
Element quality	0.6343	Min. element size	0.144
Tetrahedral elements	8894	Resolution of curvature	0.6
Triangular elements	13832	Resolution of narrow regions	0.5
Edge elements	1503	Max. element growth rate	1.5
Vertex elements	106		

4. Simulation Results

Figures 8, 9 and 10, show the upper surface of the cubic in the selected in x-y plane to study the value of the surface potential when the grid is subjected to a potential of $V = 1\ p.u.$ value as each model is studied to see the effect of increasing the number of rods of the grid also the effect of connecting the rods together on the value of the surface potential distribution.

4.1 One driven vertical rod buried in homogeneous soil.

Figure 8, represents the distribution of the potential on the surface of the grid of the first model of one rod buried in homogeneous soil that has a maximum value of the surface potential is $0.256\ p.u.$

4.2 Three driven vertical rods not connected and buried in homogeneous soil

Figure 9, represent the distribution of the potential on the surface of the grid of the second model for three rods not connected and buried in homogeneous soil that has a maximum value of the surface potential is $0.247\ p.u.$

4.3 Three driven vertical rods connected and buried in homogeneous soil

Figure 10, shows that the distribution of the potential on the surface of the grid of the third model of three rods connected and buried in homogeneous soil that has a maximum value of the surface potential is $0.1336\ p.u.$

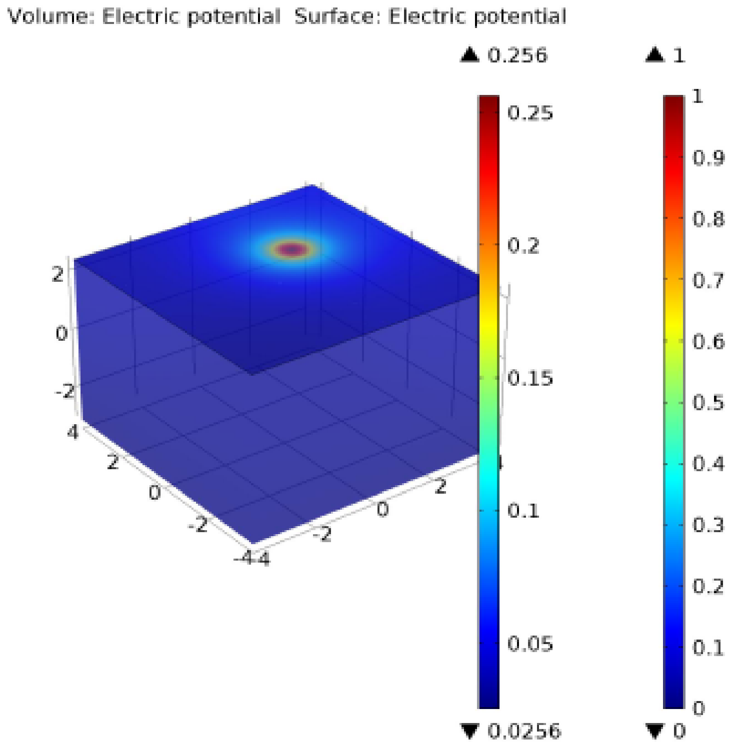

Fig. 8. The surface potential distribution of the first model.

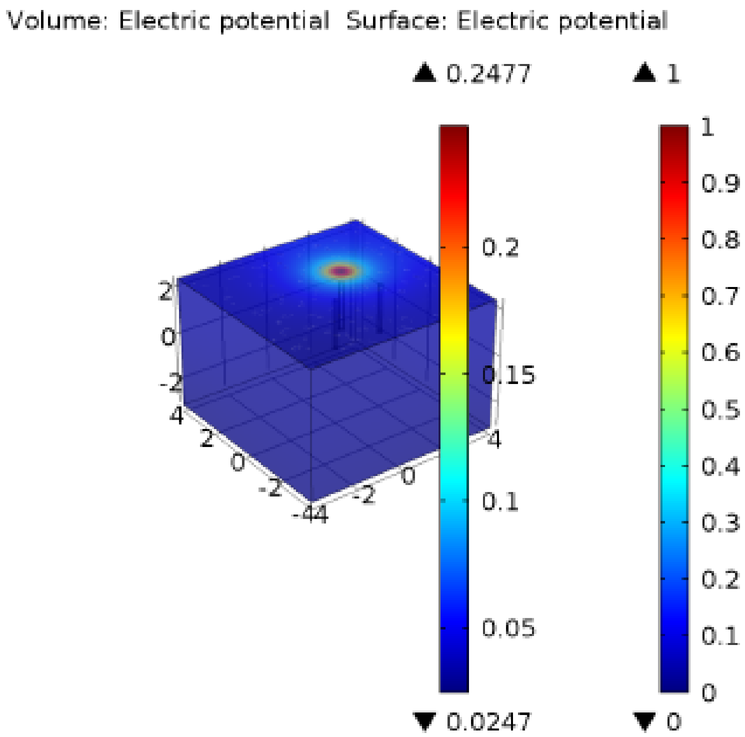

Fig. 9. The surface potential distribution of the second model.

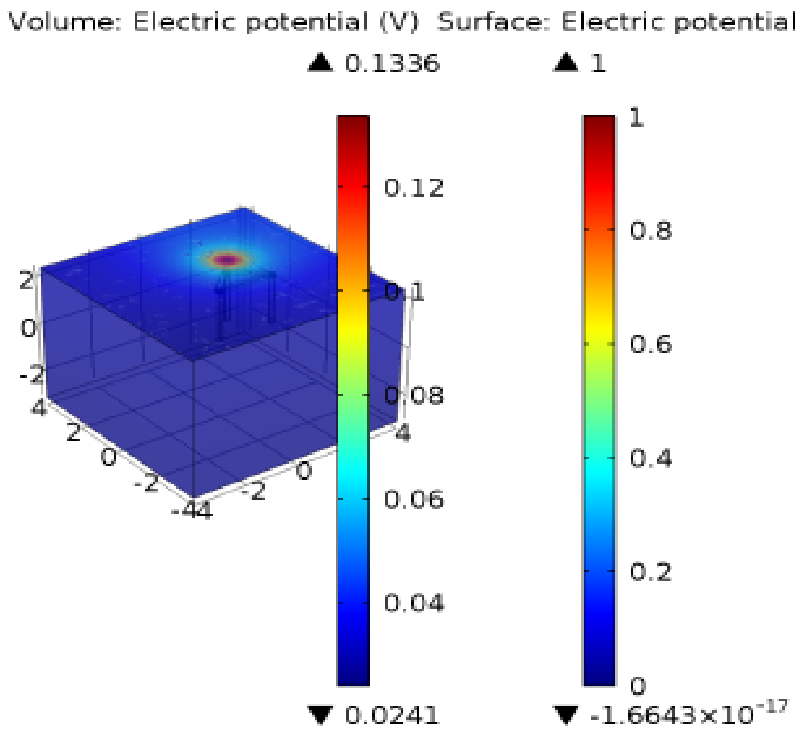

Fig. 10. The surface potential distribution of the third model.

5. Conclusion

This paper has provided a simulation technique to simulate and analyse the earthing systems of different rods numbers and connections used for estimating the surface potential at the ground surface depends on finite element method using COMSOL Multiphysics program.

The simulation results show that the more the vertical driven rods number increase, the more the value of the surface potential at the ground surface decrease, which means that it is more safety to increase the numbers of vertical driven rods in the earthing system. Also, the simulation results cleared that the benefits of connecting the vertical driven rods together, which resulting in reducing the value of surface potential distribution due to the decreasing of the whole grounding system resistance. The results explain that:

i. The maximum value of the surface potential for one driven vertical rod is $0.256\ p.u.$

ii. The maximum value of the surface potential for three driven vertical rods not connected is $0.247\ p.u.$

iii. The maximum value of the surface potential for three driven vertical rods connected is $0.1336\ p.u.$

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