Comparison Between Square and Circular Designs of Grounding Grid

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Abstract - The propose of the protection system is to protect the equipment in the power substation against large fault currents. One of the important protection system is grounding system. This paper presents a comparison between two designs of the grounding grid. The first one is a square type grounding grid and the second one is a circular type grounding grid. Firstly, the two types are assumed to be had the same total area enclosed by the ground grid, and secondary, the two types are assumed to be had the same length of the total grounding grid conductor. The parameters under study are: the grounding resistance, step voltage, touch voltage and earth surface potential. The charge simulation method (CSM) and the image method are used within this study, and the effects of the parameters such as: soil resistivity, depth of grounding grid, number of meshes and presence of the vertical rods, on the performance of grounding grids are taken into account. Finally, the validation of the simulation method is done by comparing the simulation results with the experimental results obtained in this study.

Keywords— Charge simulation method, Earth surface potential, Grounding grid, Grounding resistance, Image method, Step voltage, Touch voltage

1 Introduction

Grounding grid plays an important role in the power system protection. A safe grounding design should be had the following two main objectives.

-Provide means to carry electric currents into the earth under normal and fault conditions without exceeding any operating and equipment limits or adversely affecting continuity of service.

-Assure that a person in the vicinity of grounded facilities is not exposed to a danger of electrical shock.

The grounding resistance of grounding system must be low enough to assure that fault currents dissipate mainly through the grounding system into the earth, while maximum potential difference between close points into the earth's surface must be kept under certain tolerances (step, touch, mesh voltages).

Some of parameters can be calculated by simplifying assumptions such as grounding resistance and some of these parameters are difficult to be calculated by simplified method but they are determined by analytical expression [1].

Recent papers have proposed and calculated the earth surface potential, touch voltage, step voltage, grounding resistance by using the charge simulation method [2-5].

This paper will present three types of circular grounding grids and comparing them with three types of square grounding grids, then calculating the parameters of grids. Studying the effect of vertical rods, soil resistivity, depth of grounding grid not only on decreasing the grounding resistance but also on reducing the earth surface potential, touch voltage and step voltage are investigated.

The paper is organized as follows: Section 2 describes the charge simulation method, and how the required parameters are calculated. Section 3 presents the results of the two suggested grounding grid models and discussion. In section 4, the validation of the simulation results is done by comparing some simulation results with the experimental results obtained in this study. Finally, section 5 presents the mean conclusion of this study.

2 Charge Simulation Method

In the charge simulation method, the actual electric field is simulated with a field formed by a number of discrete charges which are placed outside of the region where the field solution is desired. Values of the discrete charges are determined by satisfying the boundary conditions at a selected number of counter points. Once the values and the positions of simulation charges are known, the potential and field distribution anywhere in the region can be computed easily [6].

If several discrete charges of any type (point, line, or ring) are presented in a region, the electrostatic potential at any point *C* can be found by summation of the potentials resulting from the individual charges as long as the point *C* does not reside on any one of these charges. Let $\boldsymbol{Q_j}$ be a number of *n* individual charges and $\boldsymbol{\varphi_i}$ be the potential at any point *C* within the space. According to superposition principle the potential at any point *C* is obtained from the following relation:

$$\boldsymbol{\varphi_i = \sum_{j=1}^{n} P_{ij}Q_j} \quad (1)$$

Where $\boldsymbol{P_{ij}}$ are the potential coefficients which can be evaluated analytically for many types of charges by solving Laplace or Poisson's equations, $\boldsymbol{\varphi_i}$ is the potential at $\boldsymbol{i^{th}}$ contour (evaluation) point, and $\boldsymbol{Q_j}$ is the charge at $\boldsymbol{j^{th}}$ point charge.

By assuming the ground surface is flat, the method of images can be used with the charge simulation method and hence, the potential will be characterized for being constant on the grounding grid and its symmetry grid [2-4]. The potential coefficients will be as follows:

$$\boldsymbol{P_{ij} = \frac{1}{4\pi\varepsilon}\left[\frac{1}{d_{ij}} + \frac{1}{d'_{ij}}\right]} \quad (2)$$

Where $\boldsymbol{d_{ij}}$ is the distance between a contour point $\boldsymbol{i}$ and a point charge $\boldsymbol{j}$ and $\boldsymbol{d'_{ij}}$ is the distance between a contour point $\boldsymbol{i}$ and an image point charge $\boldsymbol{j}$ as shown in Figure (1). As shown in Figure (1), the fictitious charges are taken to be point charges, and are located at the center of the conductors of the grid. Also, some contour points as well as some check points are assumed located on the surface of the conductor of the grid.

The positions of each point charge, each contour point and each check points are determined in ***X, Y, Z*** coordinates where the distances between the contour points or the check points and the charge points are calculated as follows:

$$\boldsymbol{d_{ij} = \sqrt{(X_j - X_i)^2 + (Y_j - Y_i)^2 + (Z_j - Z_i)^2}}$$

Where $\boldsymbol{X_j, Y_j, Z_j}$ are the dimensions of the point charges, and $\boldsymbol{X_i, Y_i, Z_i}$ are the dimensions of the contour points or the check points. In this study $\boldsymbol{\varphi_i}$ is assumed equal to one volt at each contour point, and the equation (1) is solved to obtain the magnitudes of simulation charges. Then a number of checked points, rather than the contour point, located on the surface of the electrodes where their potentials are also known and equal one volt, are taken to determine the simulation accuracy. Once an adequate charge system has been developed, the potential and field at any points outside the electrodes can be calculated.

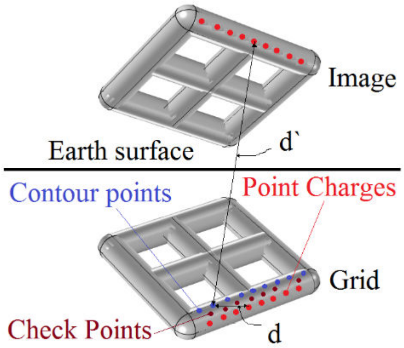

Fig. 1 Illustration of the charge simulation method

The charge simulation technique is used to obtain the ground resistance ($\boldsymbol{R_g}$), ground potential rise (GPR) and then the surface potential on the earth, due to any value of the discharging current into the center of the ground grid, is known. The touch and step voltages are calculated from surface potential. The duality expression is used to calculate the ground grid resistance ($\boldsymbol{R_g}$) from the following relations:

$$\boldsymbol{c_1 = \frac{\sum_{j=1}^{n} Q_j}{V}} \quad (3)$$

$$\boldsymbol{R_g \times c_1 = \rho \times \varepsilon} \quad (4)$$

where, $\boldsymbol{c_1}$ is the capacitance of the grounding grid (Farad), $\boldsymbol{V}$ is the GPR that is defined as 1 V [3-4], $\boldsymbol{Q_j}$ is the charge of point charge $\boldsymbol{j}$ that used for the calculation, $\boldsymbol{\rho}$ is the soil resistivity (Ohm.meter) and $\boldsymbol{\varepsilon}$ is the soil permittivity (Farad/meter).

3 Results and Discussion

It is clear that the ground potential rise (GPR) as well as the distribution of the earth surface potential (ESP) during the current flowing in the grounding system are important

parameters for the protection against the electric shock. The distribution of the earth surface potential helps to determine the step and touch voltages, which are very important for human safe.

By definition, the touch voltage is the difference between the ground potential rise (GPR) and the surface potential at the point where a person is standing while at the same time having his hands in contact with a grounded structure. While, the mesh voltage is defined as the maximum touch voltage to be found within a mesh of a ground grid. The maximum touch voltage is the difference between the GPR and the lowest potential in the grid boundary [7-11]. The maximum percentage value of $\boldsymbol{V_{touch}}$ is given as follows:

$$\boldsymbol{Max\ touch\ voltage\ \% = \frac{V_{grid} - V_{min}}{GPR} \times 100} \quad (5)$$

Where, in this equation, $\boldsymbol{V_{grid}}$ is the maximum ground potential rise (GPR), which equals the product of the equivalent resistance of the grid and the fault current [3, 12], and $\boldsymbol{V_{min}}$ is the minimum surface potential in the grid boundary. Furthermore, the maximum step voltage of a grid will be the highest value of step voltages of the grounding grid. The maximum step voltage can be calculated by using the slope of the secant line. The maximum step voltage occurs outside the grid boundary, where the slope of the recorded surface potential against distance is a maximum [5]. In the following cases, the discharging current is assumed to be 1000 A.

A. Square grounding grid

In this section, the parameters of the square grounding grid are calculated. Then the effects of the presence of vertical rods, soil resistivity and depth of grounding grid not only on decreasing grounding resistance but also on the reducing of the earth surface potential, touch voltage and step voltage are investigated. The characteristics of the square grounding grids are: the area is 35.44 m×35.44 m, the radius of grid electrode is 0.005 m, the depth of the grid is 0.5 m, the length of the vertical rod is 2 m, the radius of the vertical rod is 0.0125 m, the soil resistivity is 400 ohm.m and the total ground potential rise (GPR) is defined as 1 V. The cases under study are shown in Figure (2), which have the same area and various number of meshes.

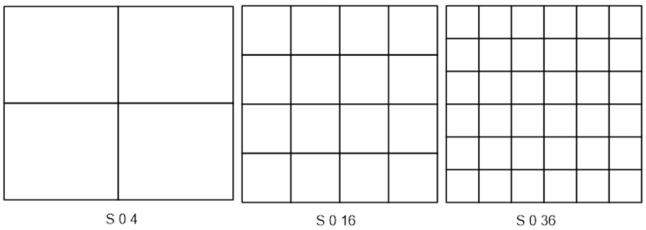

Fig. 2 Square grounding grids with different meshes

According to the charge simulation method technique the number of charges is optional, depends on the accuracy of the simulation. In our study the number of simulation charges in every case is illustrated in table (1).

Table (1)
Number of simulation charges in every case

Case	C 4	C 16	C 32	S 4	S 16	S 32
No. of charges	4397	6785	7165	3597	4985	5845

Figure (3) presents the error that calculated on the check points.

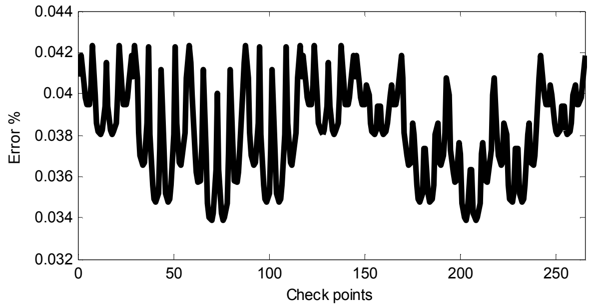

Fig. 3 Error along the check points

Figure (4) shows the profile of the earth surface potentials of 36 meshes square grounding grids as an example. Figure (5) shows the effect of the number of meshes on the earth surface potential along the diagonal of the square grounding grids of various number of meshes. It is seen that an increase in the number of meshes makes the curve of earth surface potential much flatter and a reduction in the grid resistance, touch and step voltages.

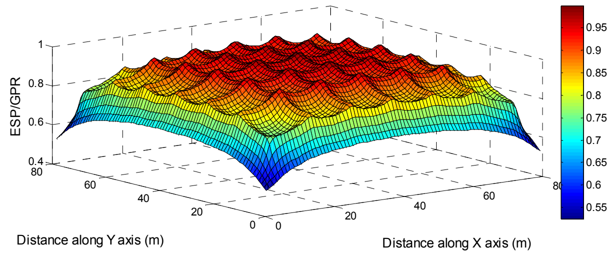

Fig 4 Voltage profile along the surface of 36 meshes square grounding grid

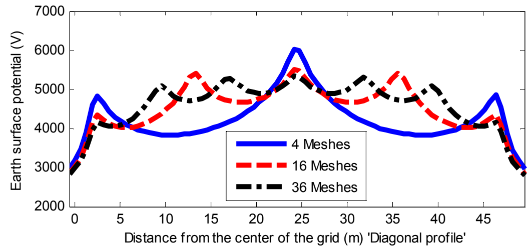

Fig 5 Earth surface potential along the diagonal of the square grounding grids of various number of meshes

Figures (6) and (7) show the effect of increasing the number of mesh on decreasing of the touch voltage and the step voltage of the square grid, respectively.

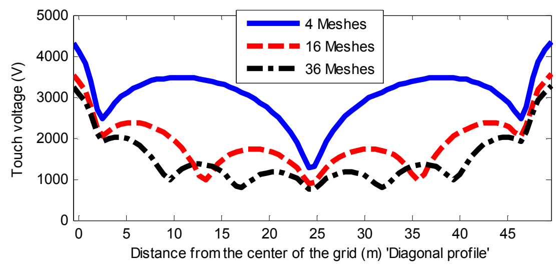

Fig 6 Effect of the number of meshes on the touch voltage of the square grounding grids

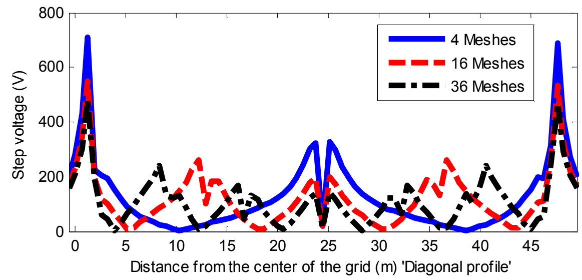

Fig 7 Effect of the number of meshes on the step voltage of the square grounding grids

Figure (8) shows the effect of vertical rods on the earth surface potential of the 36 meshes square grounding grid. In this case one rod is erected at each node of the grid. It is seen that the earth surface potential along the diagonal of the grid is slight decreased when the vertical rods are connected to the grid. Figure (9) shows the effect of vertical rods on the touch voltage of the 36 meshes square grounding grid. In this figure the touch voltage is calculated at each point along the diagonal of the grid. Also, it is seen that the touch voltage is slight decreased when the vertical rods are erected at each node of the grid.

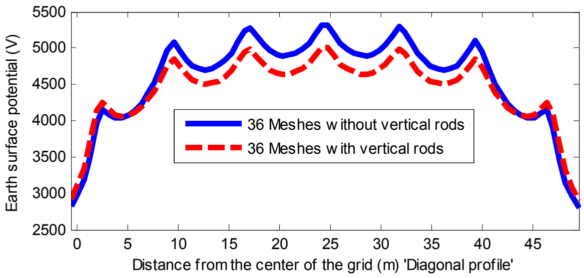

Fig 8 Effect of vertical rods on the earth surface potential of 36 meshes square grounding grid

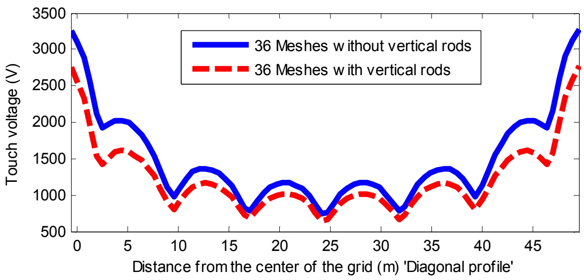

Fig 9 Effect of vertical rods on the touch voltage of 36 meshes square grounding grid

Figure (10) shows the effect of the soil resistivity values on the earth surface potential of the square grounding grid. It is seen that the decrease of the value of the soil resistivity decreases the earth surface potential. Figure (11) proves that the depth of the grid plays an important role in decreasing the earth surface potential.

Table (2) explains the effect of the number of meshes on the resistance, ground potential raise, touch voltage, and the step voltage of square grounding grids with and without vertical rods. It is noticed that increasing the number of meshes of grounding grids decreases the values of the grid resistance, ground potential raise, the touch voltage and the step voltage. Also, table (2) contains the total length of the conductors used in each grounding grid, which should be taken into account.

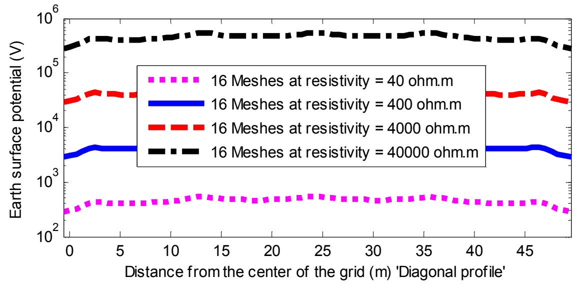

Fig 10 Effect of soil resistivity on the earth surface potential of 16 meshes square grounding grid

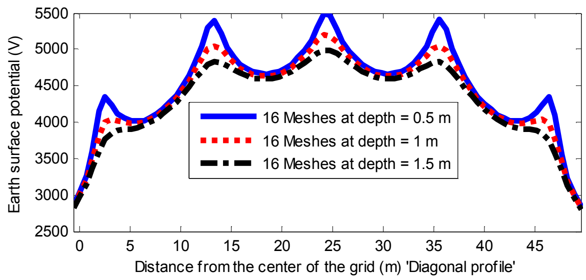

Fig 11 Effect of grid depth on earth surface potential of 16 meshes square grounding grid

Table (2)

Total conductor length, ground resistance, ground potential raise, touch voltage and step voltage of different square grounding grid cases

Grid	L_t(m)	R_g (Ohm)	GPR (kV)	V_t max % of GPR	V_s max % of GPR
S 0 4	212.69	7.29	7.29	33.8	12
S 0 16	354.49	6.39	6.39	32.1	11.6
S 0 36	469.28	6.078	6.078	31	11
S 0 4 v	220.69	7.0892	7.0892	30.60	11
S 0 16 v	386.49	6.0344	6.0344	28.1	10.5
S 0 36 v	541.28	5.6644	5.6644	26.9	9.5

* Where (S04), (S016), and (S036) are the 4, 16, and 36 meshes square grounding grids without vertical rods; and (S04v), (S016v), and (S036v) are the 4, 16, and 36 meshes square grounding grids with vertical rods.

Table (3) shows a comparison between the values of the square grounding grid resistances obtained by charge simulation method and those obtained by other formula [1]. It is noticed that there is a good agreement between the results.

Table (3)
Grounding grid resistance obtained by CSM and other formula [1]

Grid	Dwight [1]	Laurent [1]	Sverak [1]	CSM
S 0 4	5	6.88	6.77	7.29
S 0 16	5	6.02	6.12	6.39
S 0 36	5	5.80	5.70	6.078
S 0 4 v	5	6.812	6.70	7.0892
S 0 16 v	5	6.034	5.93	6.0344
S 0 36 v	5	5.73	5.63	5.6644

B. *Circular grounding grid*

In this section, the parameters of circular grounding grid are calculated. Then the effects of the presence of the vertical rods, soil resistivity and depth of grounding grid not only on decreasing grounding resistance but also on the reducing of the earth surface potential, touch voltage and step voltage are investigated. The characteristics of the circular grounding grids are: the diameter of circle is 40 m, the radius of the grid electrode is 0.005 m, the depth of the grid is 0.5 m, the length of the vertical rod is 2 m, the radius of the vertical rod is 0. 0125 m, the soil resistivity is 400 ohm.m and the total ground potential rise (GPR) is defined as 1 V. The cases under study are shown in Figure (12).

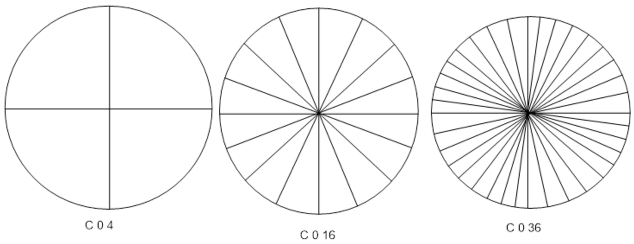

Fig. 12 Circular grounding grids with different meshes

Figure (13) shows the profile of the earth surface potentials of 36 meshes circular grounding grids. Figure (14) shows the effect of the number of meshes on the earth surface potential along the diagonal of the circular grounding grids of various number of meshes. It is seen that an increase in the number of meshes makes the curve of earth surface potential much flatter and a reduction in the grid resistance, touch and step voltages.

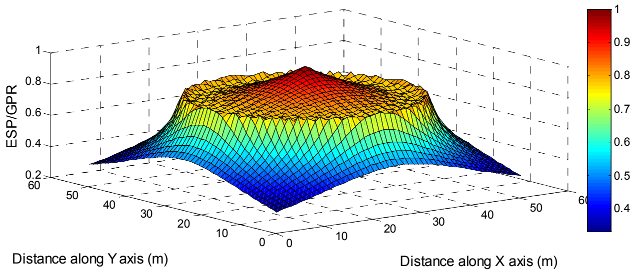

Fig 13 Voltage profile along the surface of 36 meshes circular grounding grid

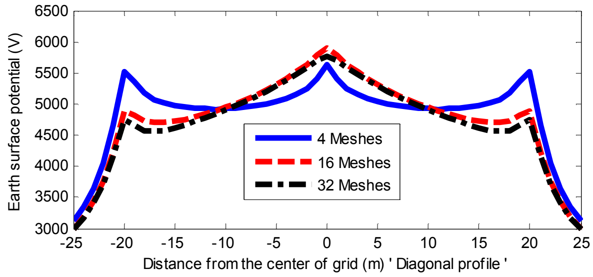

Fig 14 Earth surface potential along the diagonal of the circular grounding grids of various number of meshes

Figures (15) and (16) show the effect of increasing the number of mesh on decreasing of the touch voltage and the step voltage of the circular grid, respectively.

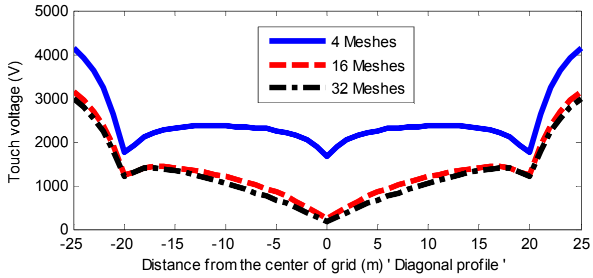

Fig 15 Effect of the number of meshes on the touch voltage of the circular grounding grids

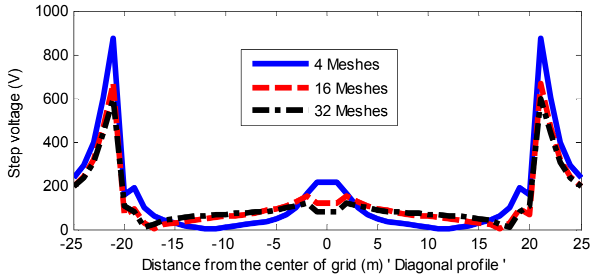

Fig 16 Effect of the number of meshes on the step voltage of the circular grounding grids

Figure (17) shows the effect of vertical rods on the earth surface potential of the 36 meshes circular grounding grid. It is seen that the earth surface potential is slight decreased when the vertical rods are connected to the grid. Figure (18) shows the effect of vertical rods on the touch voltage of the 36 meshes circular grounding grid. Also, it is seen that the touch voltage is slight decreased when the vertical rods are connected to the grid.

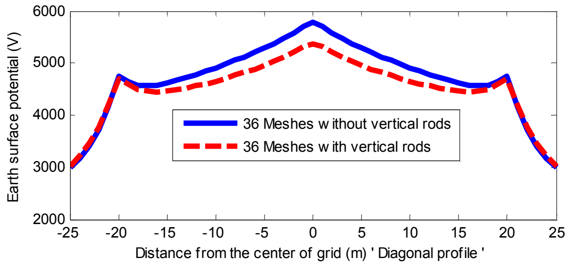

Fig 17 Effect of vertical rod on the earth surface potential of 36 meshes circular grounding grid

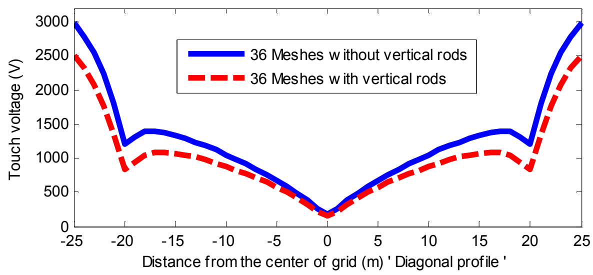

Fig 18 Effect of vertical rod on the touch voltage of 36 meshes circular grounding grid

Figure (19) shows the effect of the soil resistivity values on the earth surface potential of the circular grounding grid. It is seen that the decrease of the value of the soil resistivity decreases the earth surface potential. Figure (20) proves that the depth of the grid plays an important role in decreasing the earth surface potential.

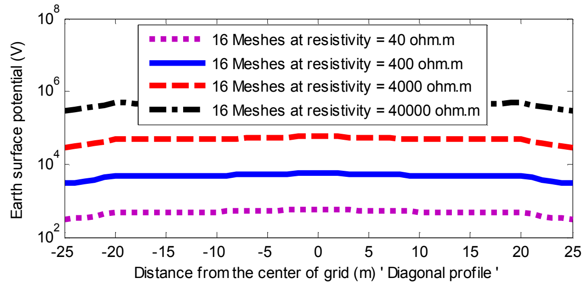

Fig 19 Effect of soil resistivity on the earth surface potential of 16 meshes circular grounding grid

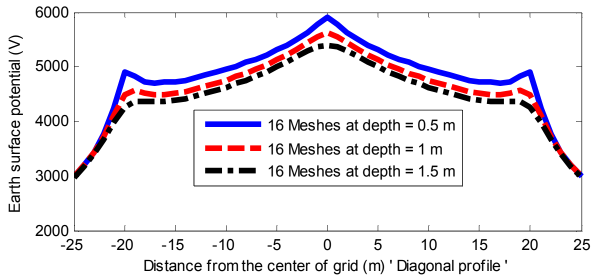

Fig 20 Effect of grid depth on the earth surface potential of 16 meshes circular grounding grid

Table (3) explains the effect of the number of meshes on the grid resistance, ground potential raise, touch voltage and the step voltage of circular grounding grids with and without vertical rods. It is noticed that increasing the number of meshes of grounding grids decreases the values of the grid resistance, ground potential raise, the touch voltage and step voltage. Also, table (4) contains the total length of the conductors used in each grounding grid, which should be taken into account.

Table (5) shows a comparison between the values of the circular grounding grid resistances obtained by charge simulation method and those obtained by other formula [1].

Table (4)

Total conductor length, ground resistance, ground potential raise, touch voltage and step voltage of different circular grounding grid cases

Grid	L_t(m)	R_g (Ohm)	GPR (kV)	V_t max % of GPR	V_s max % of GPR
C 0 4	205.66	7.28	7.28	24	12.2
C 0 16	445.66	6.14	6.14	20.3	10.84
C 0 36	845.66	5.95	5.95	20.2	10.01
C 0 4 v	213.66	7.1565	7.1565	22.4	12.19
C 0 16 v	477.66	5.8987	5.8987	16.72	10.66
C 0 36 v	917.66	5.5302	5.5302	14.97	9.36

*Where (C04), (C016), and (C036) are the 4, 16, and 36 meshes circular grounding grids without vertical rods; and (C04v), (C016v), and (C036v) are the 4, 16, and 36 meshes circular grounding grids with vertical rods.

Table (5)

Grounding grid resistance obtained by CSM and other formula [1].

Grid	Dwight [1]	Laurent [1]	Sverak [1]	CSM
C 0 4	5	6.94	6.8	7.28
C 0 16	5	5.89	5.79	6.14
C 0 36	5	5.47	5.36	5.95
C 0 4 v	5	6.87	6.76	7.1565
C 0 16 v	5	5.83	5.73	5.8987
C 0 36 v	5	5.43	5.33	5.5302

Comparison between circulargrounding grid and squaregrounding grid

In this paragraph, a comparison between the results of the square grounding grid and circular grounding grid is done.

Firstly, the two types of the ground grids are assumed to be had the same total area enclosed by the ground grid, and secondary, the two types are assumed to be had the same length of the total grounding grid conductor.

Table (6) shows a comparison between the results of both the square grounding grid and circular grounding grid, which have the same total area enclosed by the ground grid.

It is seen that the circular grounding grids give low grounding resistance, step voltage and touch voltage than those of the square grounding grids of the same total area.

Table (6)
Comparison between the results of the circular grounding grid and the square grounding grid which have same area

Grid	L_t(m)	R_g (Ohm)	GPR (kV)	V_t max % of GPR	V_s max % of GPR
C 0 4	205.66	7.28	7.28	24	12.2
C 016	445.66	6.14	6.14	20.3	10.84
C 0 36	845.66	5.95	5.95	20.2	10.01
C 0 4 v	213.66	7.1565	7.1565	22.4	12.19
C 0 16 v	477.66	5.8987	5.8987	16.72	10.66
C 0 36 v	917.66	5.5302	5.5302	14.97	9.36
S 0 4	212.69	7.29	7.29	33.8	12
S 0 16	354.49	6.39	6.39	32.1	11.6
S 0 36	469.28	6.078	6.078	31	11
S 0 4 v	220.69	7.0892	7.0892	30.60	11
S 0 16 v	386.49	6.0344	6.0344	28.1	10.5
S 0 36 v	541.28	5.6644	5.6644	26.9	9.5

Secondary, the two types are assumed to be had the same length of the total grounding grid conductor. Table (7) shows a comparison between the results of both the square grounding grid and circular grounding grid, which have the same length of the total grounding grid conductor.
It is noticed that it is difficult to explain the effect of the total grounding grid conductor alone without taken into account the area of the grid. In other word, the effect of the non-uniform conductors' distribution within the grid area has an important role in the reducing the grid resistance, and should be studied carefully.

Table (7)
Comparison between the results of the circular grounding grid and the square grounding grid, which have the same total length

Case	L_t(m)	R_g (Ohm)	GPR (kV)	V_t max % of GPR	V_s max % of GPR	Total area
C 0 4	205.66	7.28	7.28	24	12.2	1256.63
C 016	445.66	6.14	6.14	20.3	10.84	1256.63
C 0 36	845.66	5.95	5.95	20.2	10.01	1256.63
C 0 4 v	213.66	7.1565	7.1565	22.4	12.19	1256.63
C 0 16 v	477.66	5.8987	5.8987	16.72	10.66	1256.63
C 0 36 v	917.66	5.5302	5.5302	14.97	9.36	1256.63
S 0 4	205.66	7.47	7.47	33.7	13	1174.93
S 0 16	445.66	5.39	5.39	35.1	10.6	1986.16
S 0 36	845.66	4.015	4.015	38.3	9.31	3648.709
S 0 4 v	213.66	7.257	7.257	30.33	10	1174.93
S 0 16 v	477.66	5.110	5.110	30.2	8.3	1986.16
S 0 36 v	917.66	3.6758	3.6758	29.2	8.6	3648.709

4 Validation of the Simulation Method

In this section the validation of the simulation results is done by comparing some simulation results with the experimental results obtained in this study.
Figure 20 shows the components of experimental setup, which contain, electrolytic tank makes from glass and has dimensions of 1m × 1m × 0.5 m. The inner surface of the tank is covered by conducting sheath. Tap water is used as an electrolyte, and represents a homogenous soil. Its electric resistivity is 33.4 Ωm. The electrolytic resistivity can be changed by changing the salinity of the tap water [13-14].

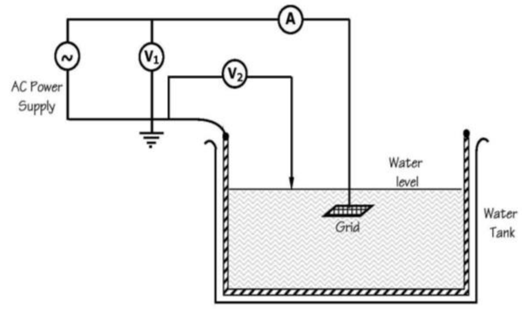

Fig 21 Experimental setup

A power supply ranges from zero to 380 is used to change applied voltage up to appropriate value.

A voltmeter is used to measure the voltage that output from the auto transformer and applied to the model of grounding grid (V_s). The magnitude of applied voltage is considered to be constant during the different tests, it is fixed at value equals to 100 volt in all cases.

Another voltmeter is used to measure the surface potential (V_m), i.e along the diagonal of the grid in this tests.

An ammeter is used to measure the current that following through the electrolyte between the model grid and the return electrode. For a scale factor 100:1, variety of grids with outside dimensions of 20 cm × 20 cm have been modeled and tested.
Figures (21) and (22) show a comparison between the experimental result and charge simulation method results of a square ground grid of four meshes and circular ground grid of four meshes, respectively. It is seen that there is a good agreement between the results of the two methods.

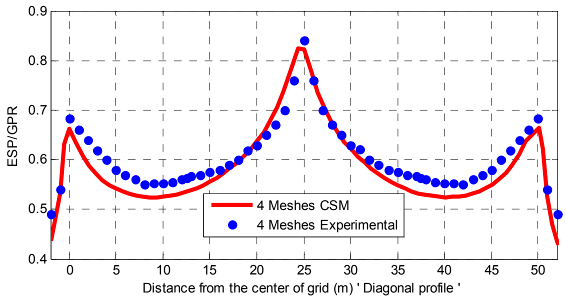

Fig .22 Earth surface potential of 4 meshes square grounding grid

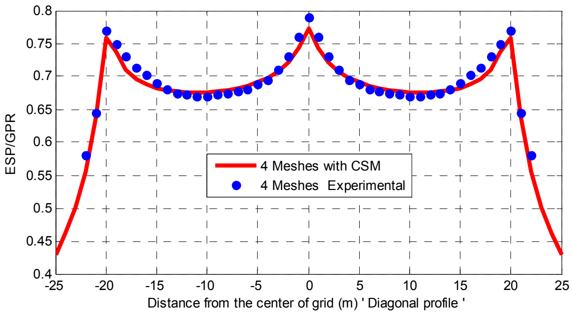

Fig .23 Earth surface potential of 4 meshes circular grounding grid

Table (8) shows a comparison between the values of the grounding grid resistances obtained by experimental method and those obtained by other formula [1] and simulation method. It is noticed that there is an acceptable agreement between the results.

Table (8)
Grounding grid resistance obtained by experimental, CSM and other formula [1]

Grid	Dwight [1]	Laurent [1]	Sverak [1]	CSM	Experimental
S 0 4	0.417605	0.5745	0.5549	0.6093	0.4761
S 0 16	0.417605	0.51185	0.4921	0.5338	0.4347
C04	0.4175	0.5795	0.56016	0.6102	0.46511
C016	0.4175	0.492444	0.47270	0.5132	0.4166

* Where (S04) and (S016) are the 4, and 16 meshes square grounding grids without vertical rods; and (C04) and (C016) are the 4 and 16 meshes circular grounding grids without vertical rods.

5 Conclusions

In this paper, a comparison between two types of grounding grid (square grounding grid and circular grounding grid) is introduced.

The charge simulation method (CSM) and the image method are used in this study. The validation of these methods is satisfied by a comparison between their results and the results obtained by the formula of the IEEE standard. The charge simulation method with the image method give a good agreement with the IEEE standard formula.

A comparison between the results of the circular grounding grid and square grounding grid is done. From the obtained results, it is noticed that the number of meshes plays an important role in reducing the grid resistance, the step voltage and the touch voltage. Also, it is found that there is a slight reduction on the earth surface potential when a set of a vertical rods are connected to the grid. Also, increasing the depth of the grounding grid decreases the grid resistance, the step voltage and the touch voltage.

Also, the circular grounding grid offers good values of the grounding grid parameters (grid resistance, step and touch voltages) compared with the square grounding grid when they have the same total area.

Finally, the results of the experimental model shows that the experimental scale model can be effectively used to study the parameters of the grounding grid design.

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