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Grounding Characteristics Estimations of Wind Turbine Using ANN

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Abstract

The purpose of the grounding system is to achieve the safety of the individuals and equipment during the faults through dissipation of the discharging current into the earth. In addition, it maintains the continuity of the power system to avoid the undesirable outage of the system equipment. In IEEE Standard 80-2000, the grounding resistance, touch and step voltages are based on empirical formulas. In this paper, an artificial neural network (ANN) model is constructed to predict the magnitude of the grounding resistance (R_g) as well as the touch and step voltages respectively, based on the grid configuration such as the side length of the grid and the number of grid meshes. The training data of ANN are obtained from the numerical methods (Extremal charge method (ECM) and Extremal current method (EIM)) that are used to determine R_g and earth surface potential (ESP) of one and two-layer soil respectively. The proposed grounding system design was used as a grounding system of wind turbine. An ANN model is very preferable due to the complexity of the numerical method to compute R_g and ESP, especially in case of multi-layer soil, in addition, it helps to reduce the computation time. The test data results refer to the ability of the ANN model to substitute the complex software to calculate R_g and ESP.

Keywords: Grounding system, Wind farm, Earth surface potential, Extremal current method, Neural networks.

I. INTRODUCTION

The importance of the power plants and substation's grounding is enhanced in the last few years for the safety and reliability purposes [1]. The purpose of grounding system in any installation specially for the wind towers is the ability to carry and dissipate the fault current into earth without changing the operating limits of the system equipment. The wind towers encountered lightning strickes which carry a large amount of current with few hundared kA. In addition, it maintains the continuity of the system power flow to avoid the undesirable outage of the system equipment. Furthermore, it ensures the individuals and equipment safety. The effective grounding grid design must meet the requirement regulations of IEEE Std.80-2000 and satisfy the economical solution [2]. The maximum step and touch voltages due to discharging current into the grounding system must be lower than the safe limits in the technical standards (IEEE Std.80-2000) [3].

The touch and step voltages are determined from the known earth surface potential (ESP) due to flowing the discharging current into grounding grids. In addition, the geometrical dimension of the grounding grids and the soil resistivity affects these voltages. Moreover, their values must be lower than the safe limits as in IEEE Std.80-2000. The extremal charge method (ECM) for one-layer soil and extremal current method (EIM) for two-layer soil is used to determine the grounding resistance (R_g) and the ESP [4].

Determination of the grounding resistance (R_g) and earth surface potential (ESP) using the above mentioned methods are time consumed and to reduce the efforts that exerted to calculate R_g and touch and step voltages, the neural network model is used. The neural network model is now used in updating researches as a tool to detect the R_g, for any grounding rods and grids.

Androvitsaneas et al., [5], presented an ANN mathematical approach to estimate the R_g for any grounding system, embedded in various ground enhancing compounds. The field measurements such as soil resistivity within various depths and of rainfall height during some periods of time, like last week and last month and estimates the ground resistance value of the tested rods are used as training data. Some ANN algorithms are constructed and comparing between each other to select which one with high accuracy between the experimental data and estimated data. Regarding the ANN methodology that used in this work, there is no particular algorithm which gives the best results for all cases and tasks. There is a suitable algorithm with best performance depending on the number of outputs that must be estimated. Thus, more investigation is necessary in emerging the most suitable algorithm.

Asimakopoulou et al., [6] developed Artificial Neural Networks (ANNs) model to investigate the estimation of the variance of ground resistance of the vertical rods throughout the year. The experimental data of soil resistivity, ground resistance, and rainfall were trained, validated and tested by the ANN model with different training algorithms to select the optimum training algorithm and the respective parameters. In addition, predict the behavior of the ground resistance of a

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single rod. This work was used only to predict the grounding resistance of the grounding rod, which is not suitable for large substation.

Salam et al., [7] presented the ANN model to predict the relation between the grounding resistance and rod length that buried in the soil based on the experimental field data. The model results refer to a good agreement between the prediction and experimental data. The least square errors were 0.995 and 0.925 for the training and testing sets respectively. This work focused on the vertical rod, which may be impractical in the case of large substation, then it need to apply the ANN on the grounding grids which were efficiently as a grounding system for large substation.

Gouda et al., [8] addressed several ANNs to evaluate apparent soil resistivity and design parameters of grounding system of predetermined values of grounding resistance and soil resistivity without using complicated calculations. In this work, many ANN algorithms were used to carry out the grounding grid design and this made the design was complex. In addition, it didn't take into consideration, the role of the step and touch voltages in the grounding grid design which must not exceed the permissible safe limit values.

The proposed work aims to develop an ANN model that is not only predicted the grounding resistance, but also the touch and step voltages for grounding grids with a specified regular shape (square and rectangle) without need to running a consumed time software. The training data is collected using owned software based on numerical methods in [4] to calculate the grounding resistance, touch and step voltages in case of one and two-layer soil. The numerical methods are the ECM and EIM, these methods are explained in detail in the appendices A, B and C. The results of the ANN referred to the ability of the model to predict the R_g, V_t and V_s with small errors.

II. GROUNDING SYSTEM FOR WIND TURBINES

Wind turbine grounding system must be effectively designed to prevent the damage of the wind turbine due to the excessive high lightning currents. The grounding system of the wind turnbine must save safe limits of the touch and step voltages by decreasing the grounding resistance of the grounding installation. The grounding resistance of the wind turbine must to be 10 Ω or less to be suitable for lightning protection. In order to represent a grounding for wind turbine, a ring electrode places around the foundation and bonding with the turbine tower [9]. A typical grounding system of the wind turbine can be developed as in Fig. 1 [10, 11]. The grounding system in the current study was taken as square and rectangle grounding grids to make the calculation of grounding resistance, step and touch voltages easier. Some other grounding grid configurations were used as a grounding system for the wind turbines and was shown in Fig. 2. A numerical method such as ECM and EIM were used to calculate the grounding resistance, step and touch voltages of the proposed square and rectangle grounding grids as in Fig. 3.

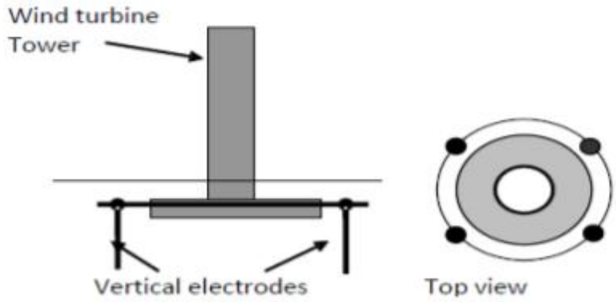
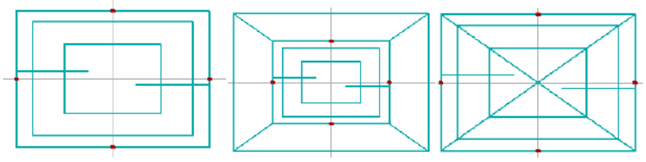


Fig. 1 Typical wind turbine grounding layout [10, 11]



(a) (b) (c)

Fig. 2 alternative grounding systems for wind turbines [9]

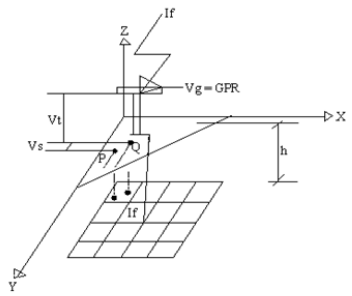


Fig. 3 Grounding system parameters, the ground potential rise (GPR), the fault current (I_f), the touch voltage (V_t), the step voltage (V_s) and grid depth (h) that computed to the proposed square grid [12]

III. GROUNDING RESISTANCE, STEP AND TOUCH VOLTAGES

When the fault current or lightning discharges in the grounding grid that was buried in the soil, the earth surface potential appeared on the earth's surface and causes the presence of step and touch voltages. These voltages must be in a safe limit, where, exceeding this limit will result in a catastrophic danger to the individuals and animals in the area surrounding the grounding grid. In this section, the method to calculate the grounding resistance (R_g) and the earth surface potential (ESP) is presented.

A. *For homogenous soil*

The extremal charge method (ECM) was used to determine R_g and ESP for the grounding grid in the homogenous soil. This method was based on the distribution of point charges along the axis of the grid conductors which were considered as unknown charges *Q*. The contour points with known voltage *V* was assumed on the surface of the conductors. Based on the image method, the image grid was assumed in the air at the distance from the earth's surface equal to the depth of the grid and other fictitious charges with the same polarity of the charges on the original grid conductors. Calculating the distances between each contour point on the surface of the original grid conductors and the point charges on the original and image grid led to the formation of the potential matrix. This method was explained in detail in [4] and in appendix A.

B. For two layer soil

The extremal current method (EIM) was used to determine the R_g and ESP due to discharging current into the grounding grid buried in two layer soil. This method corresponds the same assumption that was taken into consideration in ECM. The current sources were used instead of the point charges that used in ECM. The method was based on satisfying the boundary conditions for the contour points on both grounding conductors and vertical rods. The applied voltage realigned the dipoles in the two soils (Soil 1 and Soil 2 as in Fig. B1) so the computation of the electric field in the case of two layer soil became a complex process. In this method, a fictitious current sources were used to simulate the grid conductors, in addition to soil 1 and soil 2. The contour points were assumed on the surface of grounding conductor and the vertical rods, furthermore, the contour points were assumed also on the interface surface between the two soils. For the contour points on the interface surface, the potential as well as the normal component of current density must be the same from the boundary side (soils 1 and 2). This method was demonstrated in detail in [4] and appendix B.

The complex computation of the grounding resistance and the earth surface potential in the case of two layer soil or multilayer soil inspire us to construct a model using artificial neural network (ANN) to predict the grounding resistance, touch and step voltages (V_t and V_s) based on the grid configuration (its dimension, number of meshes, and shape) at specified fault current and soil resistivity. The fault current is assumed to be 5000 A for one and two layer soil, in addition, the resistivity of the soil in ole layer soil is assumed to be 300 Ω.m and for two layer soil, the upper layer resistivity is assumed to be 2000 Ω.m and 100 Ω.m for the lower soil.

IV. ARTIFICIAL NEURAL NETWORK (ANN) USING FOR GROUNDING GRID DESIGN

An ANN was considered an information system which relied on the input and the output and the weight matrix that linked between the input and the input. It was based on the training process to create a system that predicts the output based on the previous training of the data that links between the input and the output. The neurons or the interconnected elements were the main constituents of the neural network. In order to construct the neural network, it must identify the input and the output. The input was the number of grid meshes and the side length of the grid in x and y direction and the out was the grounding resistance (R_g), the step and touch voltages (V_s and V_t). The fault current, the resistivity of the soil and the grid depth were assumed to be constant. The ANN system consists of the input layer, the hidden layer and the output layer. Good design of the ANN system leads to higher accuracy with minimum layers.

Figure 4, depicts the construction of the network architecture of ANN based on multilayer feed forward-back propagation which is a popular ANN architecture [13, 14]. The ANN architecture model for each method consists of four layer network (one input layer, two hidden layers and one output layer). A two-layer perceptron, with the same neurons in each hidden layer and Sigmoid functions, has been utilized because of the highly nonlinear data and it has a good performance when working with the back-propagation learning algorithm [15, 16]. The inputs of the ANN network are n, which in our study is 3 inputs, i_1, i_2 and i_3 refer to the number of meshes, the length of the grid conductor in x and y directions. Furthermore, the number of output is 3 and the three outputs are o_1, o_2 and o_3 which refer to the grounding resistance, touch and step voltages.

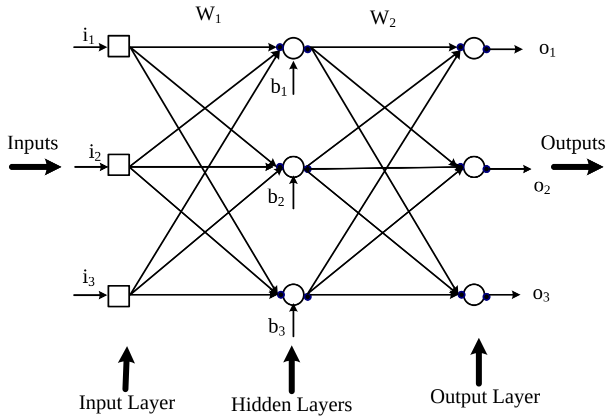


Fig. 4. Multi layer perceptron neural network training

The Sigmoid function is used to determine the output value. This Sigmoid ranges between 0 and 1. The mean square errors for the training process was assumed as 0.0001 which meant that the training process to get the weight matrix will stop when the system attained this error. The mean square error is the error between the actual values of the output and the predicted output of the neural network system.

In this study, for the homogenous soil, 4596 conditions were extracted using ECM, 2743 cases were used to train the neural network system, and 1853 samples were used as test cases. Table 1 explains the distribution of the number of samples that were used in training and testing processes according to the number of grid meshes. According to testing results, the max errors were 2.88%, 7.25%, and 2.91% for R_g, V_t, and V_s respectively. Moreover, the average errors for all test cases were 0.157%, 0.691% and 0.261% for R_g, V_t, and V_s respectively.

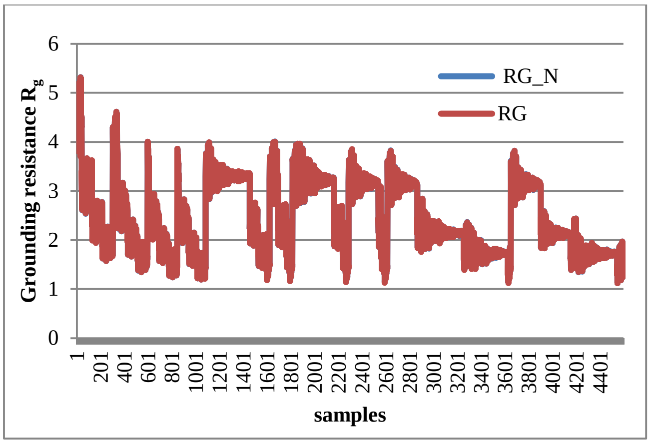
Furthermore, the comparison between the actual values of R_g, V_t, and V_s and the predicted same parameters from the neural network were shown in Fig. 5a, b, and c.

Fig. 5 shows that the agreement between the actual values of R_g, V_t and V_s with the predicted value of the same parameters using neural network for 4596 cases.

In case of two layer soil, 140 cases were used as training samples and 118 samples for testing. Table 2 illustrates the number of these samples according to the number of grid meshes. For the training samples, the maximum grid resistance is 4.9801 Ω, maximum touch voltage is 7779.8 V and maximum step voltage is 5905.9V. These values were very important since all training samples were normalized based on them. After training process, a weight matrix was developed and utilized to construct the prediction model. In order to test the accuracy of the prediction model, 118 testing data were applied as were explained in Table 2. The maximum predicted error for the testing samples was 2.3%, 4.99% and 4.99% for for R_g, V_t, and V_s respectively. Figure 6 illustrates the error percentage between the actual and predicted values of the grounding resistance, touch and step voltage. This figure explains that the less percentage error occurred in grounding resistance (R_g) where the percentage error didn't exceed 2.3%.

Table 1: Number of samples based on the number of grid meshes

Training Samples		Testing samples
No. of meshes	Number of samples	Number of samples
1	104	198
4	107	186
9	127	123
16	120	118
25	297	241
36	117	75
49	348	124
64	164	162
81	642	396
100	717	230
Total	2743	1853



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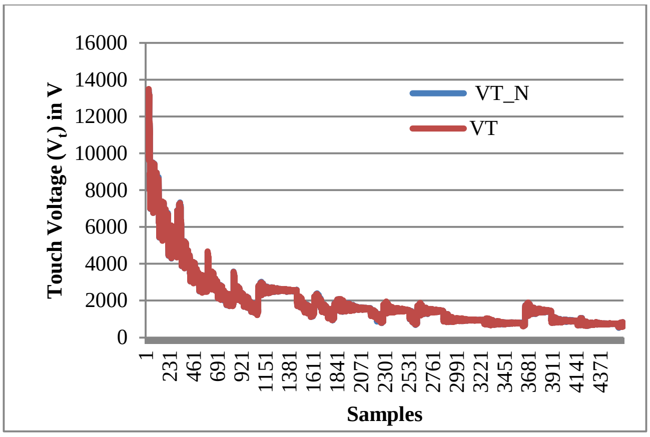

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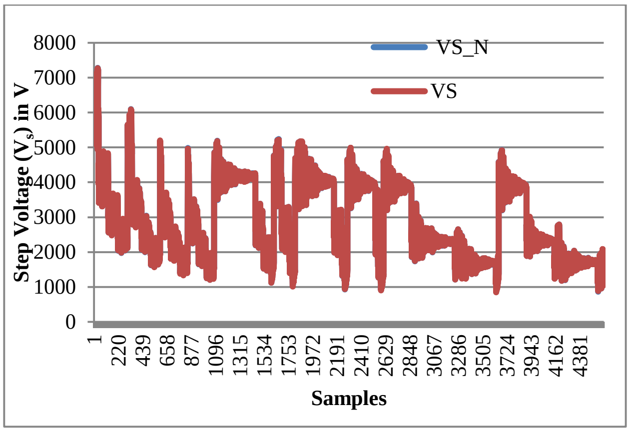

(c)

Fig. 5: comparison between the actual and predicted values of R_g, V_t, and V_s.

Table 2: Number of samples based on the number of grid meshes

Training Samples		Testing samples
No. of meshes	Number of samples	Number of samples
4	28	26
16	28	19
36	28	45
64	28	10
100	28	18
Total	140	118

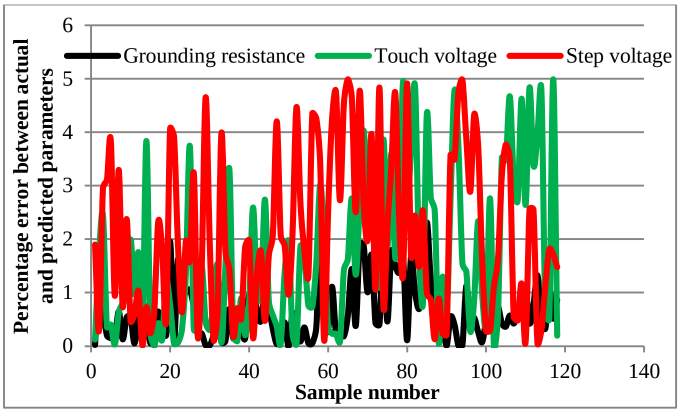

Fig. 6:Percentage error between the actual and predicted value of grounding resistance, touch and step voltages for two layer soil

V. RESULTS OF ECM AND EIM

In this section, some of ECM and EIM results were reported. Figures 7 and 8 illustrated two applied cases for homogeneous and two layer soil. Figure 7 depicted the earth surface potential per ground potential rise of the square grid (60m×60m, 16 meshes, grid depth=0.5m, no vertical rod connected to the grid, soil resistivity=300 Ω.m, grid conductor radius=0.005m) with the distance along the diagonal of the grid in m. The touch and step voltages can be calculated from the earth surface potential where, the touch voltage is the difference between the ground potential rise and the minimum voltage in the grid boundary and the maximum touch voltage was occurring in the corner mesh. In addition, the step voltage can be calculated by computing the slope of the curve outside the grid boundary and it referred to the maximum difference between two adjacent points at 1m outside the grid boundary. The comparison of grounding resistance obtained from ECM and the other grounding resistance formula in IEEE standard was in Table 3. Table 3 explains that the grounding resistance by ECM numerical solution was closed with Schwarz formula that was addressed in IEEE standard 80-2000. Figure 8 showed the earth surface potential per ground potential rise for the square grid that was buried in two layer soil. The specification of grid and the properties of the soil was as follows; (50m×50m, 16 meshes, grid depth=0.5m, ρ_1=2000 Ω.m, ρ_2=100 Ω.m, the vertical rod was connected to the grid at the perimeter of the grid, rod length=3m, conductor radius=0.005m).

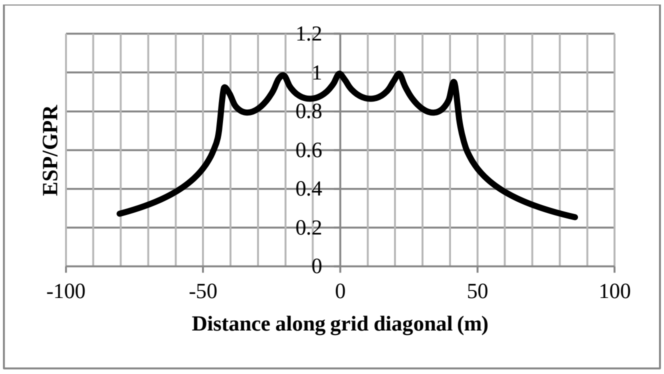

Fig.7: ESP/GPR for square grid in homogenous soil

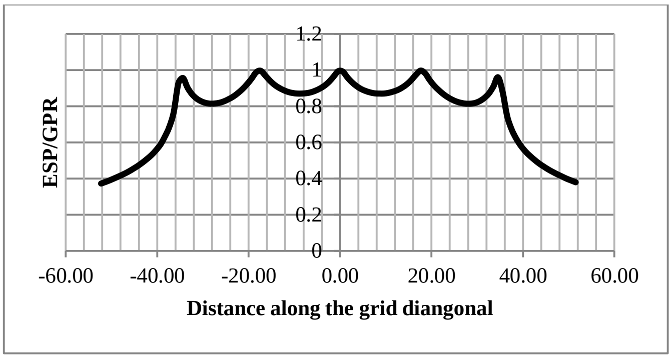

Fig.8: ESP/GPR for square grid buried on two layer soil

Table 3: Percentage error between different grounding resistance formula and ECM numerical solution

Grounding resistance computation method	Grounding resistance magnitude	Error based on Schwarz formula
Dwight formula	2.21	5.55%
Laurent Formula	2.71	15.8%
Sverak formula	2.69	14.95%
Schwarz formula	2.34	0%
ECM	2.29	2.13%

The verification of ECM and EIM was addressed in detail in appendix C. The verification was based on the work introduced in [17] for one layer soil model and in [18] for two layer soil model which was constructed based on the work presented in [4].

VI. CONCLUSIONS

More researches focused on the computation of grounding resistance, step and touch voltages due to flowing the fault currents into grounding systems. The computation of the previous parameters is very complicated and time consuming, especially in case of multilayer soil. The artificial neural network (ANN) was utilized to construct a prediction model to reduce the consumed time for evaluating the effect of parameters in a specified output. Therefore, the ANN was used for predicting the grounding resistance, touch and step voltages when some of the grid and soil parameters were known such as the grid dimensions, number of grid meshes, resistivity and permittivity of the soil, type of the soil and its structure. The constructed ANN model results indicated that the ability of the proposed model to predict the grounding resistance, touch and step voltages. Based on the model results, the maximum error between the calculated and predicted values of the output parameters doesn't exceed 5 %.

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APPENDIX A: RULING EQUATIONS FOR GROUNDING RESISTANCE, TOUCH AND STEP VOLTAGES FOR HOMOGENOUS SOIL

In order to compute the grounding resistance (R_g) and earth surface potential (*ESP*) due to the discharging current into grounding grid, which buried in homogenous soil, the extermal charge method (*ECM*) is used [4]. In this method, point charges distributed along the grid conductor axis in original and image grid. In addition, the contour points were distributed on the surface of grid conductor of the original grid. When a fault or lightning current discharges into the grid, the voltage of the contour points was known as V and when distances between each of the contour points and all of point charges on the original and image grid (P_{ij}) were determined, the point charges can be calculated as in Eqn. (A.1) as follows;

$$V_i = \sum_{j=1}^{n} P_{ij} Q_j \quad (A.1)$$

where, i refers to the contour point and j refers to point charges, V_i is the voltage of contour point i and Q_j is the charge of point charge j and P_{ij} constitutes the potential matrix which can be computed as in Eqn (A.2).

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

where, d_{ij} is the distance between contour point i and charge point j on the original grid and d'_{ij} is the distance between the contour point i on the original grid and charge point j' on the image of the grid and ε is the dielectric constant representing the soil. The distances d_{ij}, d'_{ij} can be calculated as follows;

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

$$d'_{ij} = \sqrt{(X'_j - X_i)^2 + (Y'_j - Y_i)^2 + (Z'_j - Z_i)^2} \quad \text{(A.3)}$$

where, X_j, Y_j and Z_j express the charge point coordinates and X_i, Y_i and Z_i refers to contour point coordinates.

After determining the potential matrix and knowing the voltage of contour point the charges of the point charges will be known by Eqn (A.4), therefore, the voltage at any point xx on the earth surface (V_{xx}) can be determined as in Eqn (A.5)

$$[Q_j] = [P_{ij}]^{-1}[V_i] \quad \text{(A.4)}$$

$$V_{xx} = \sum_{j=1}^{n} P_{xxj} Q_j \quad \text{(A.5)}$$

The soil can be expressed as a capacitance and its value can be computed as in Eqn (A.6) and the grounding resistance can be calculated as in Eqn (A.7).

$$C = \sum_{j=1}^{n} Q_j \Big/ GPR \quad \text{(A.6)}$$

$$R_g \times C = \rho \times \varepsilon \quad \text{(A.7)}$$

where, GPR represents the ground potential rise and assumed to be $1V$ and ρ expresses the soil resistivity. The ground potential rise can be computed by multiplying the fault current and the grounding resistance.

The touch voltage and step voltage in V can be determined as in Eqns. (A.8) and (A.9);

$$V_t = GPR - V_{min} = R_g \times I_f - V_{min} \quad (V)$$

$$V_{min} \text{ satisfies the following condition}$$

$$V_k > V_{k+1} \text{ and } V_{k+1} < V_{k+2} \quad \text{(A.8)}$$

where, k refers to the points on the earth surface.

$$V_s = max|V_k - V_{k+1}| \quad (V) \quad \text{(A.9)}$$

where, V_k and V_{k+1} are two points on the earth surface potential profile outside the grid boundary.

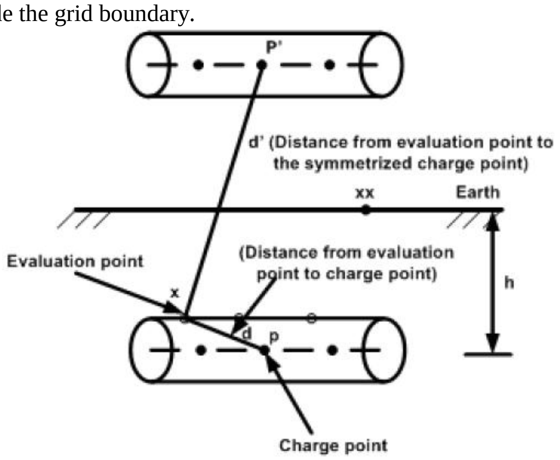

Fig. A1: distribution of the point charges and contour points to apply ECM

APPENDIX B: RULING EQUATIONS FOR GROUNDING RESISTANCE, TOUCH AND STEP VOLTAGES FOR TWO-LAYER SOIL

The grounding resistance (R_g) and earth surface potential (ESP) due to discharging current into the grounding grid, which was buried in two layer soil model, can be determined using the extermal current method (EIM). In this method, current sources were distributed on the original and the image grid conductors axis as in ECM, in addition, current sources were placed also in soil 1 and soil 2. The contour points were placed on the surface of the original grid conductors and on the interface between the two soils 1 and 2. In this method, some boundary conduction must be satisfied and it helps to determine R_g and ESP.

As in Fig. B1, the total current sources and contour points on the original and image grounding grids with vertical rods were assumed to be N_1. These current sources were divided into current sources that placed on the grid conductor and vertical rods in soil 1 and expressed as N_A and current sources that placed on the remain part of the vertical rods in soil 2 was expressed as N_B which was considered (N_1-N_A). The current sources N_1 were valid to compute the field in the two soils 1 and 2. The number of current sources in soil 1 and 2 was assumed to be N_2. The current sources on soil 1 was assumed to be (N_1+1) to (N_1+N_2) which valid for the field calculation for Soil 2 and (N_1+N_2+1) to (N_1+2N_2) for soil 2 which valid for field computation in Soil 1. The contour points on the original grid conductors and on the interface between the two soil were also assumed as N_1 and N_2. As shown in Fig. B1, the h expresses the depth of the grid in the soil and z expresses the thickness of the upper layer soil.

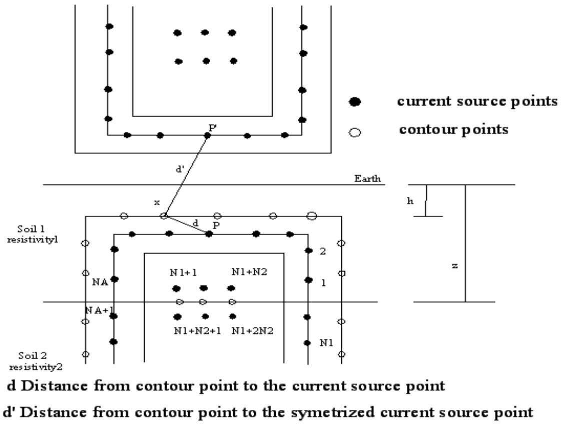

Fig. B1: Distribution of current source and evaluation points on the grounding grid and each soil for two-layer soil model.

Determining the magnitude of the currents of the current sources obeyed some of the boundary conditions. Based on Dirichlet's condition, the potential of the contour points on the original grid conductors can be computed using Eqn (B.1). Moreover, for the contour points on the soil interface, the current density and the potential from the both sides of the interface line are the same (Soil 1 and Soil 2).

For contour points 1 to N_1, the boundary condition can be expressed as follows;

$$\sum_{j=1}^{N_1} P_{a\,i,j} I_j + \sum_{j=N_!+N_2+1}^{N_1+2N_2} P_{1i,j} I_j = GPR \ldots i = 1, N_A$$

$$\sum_{j=1}^{N_1} P_{a\,i,j} I_j + \sum_{j=N_!+1}^{N_1+N_2} P_{2i,j} I_j = GPR \ldots i = N_A + 1, N_1 \quad \text{(B.1)}$$

Where,

$$P_{ai,j} = \frac{\rho_a}{4\pi}\left(\frac{1}{d} + \frac{1}{d'}\right),\ P_{1i,j} = \frac{\rho_1}{4\pi}\left(\frac{1}{d} + \frac{1}{d'}\right) \ and \ P_{2i,j} = \frac{\rho_2}{4\pi}\left(\frac{1}{d} + \frac{1}{d'}\right)$$

,

ρ_a, ρ_1& ρ_2 express the apparent resistivity and resistivity of soil 1 and 2 respectively. And ρ_a can be calculated as in [4].
For contour points N_1+1 to N_2 which lies on the soil interface, the potential continuity condition is as follows;

$$\sum_{j=N_1+1}^{N_1+N_2} P_{2i,j} I_j - \sum_{j=N_1+N_2+1}^{N_1+2N_2} P_{1i,j} I_j = 0 \ldots i = N_1+1, N_1+N_2 \qquad (B.2)$$

For normal current density continuity condition J_n:

$$J_{n1}(i) - J_{n2}(i) = 0 \ for\ i = N_1+1, N_1+N_2 \qquad (B.3)$$

Eqn. (B.3) can be rewritten as in Eq. (B.4):

$$\left(\frac{1}{\rho_1} - \frac{1}{\rho_2}\right)\sum_{j=1}^{N_1} F_{a\perp i,j} I_j - \frac{1}{\rho_2}\sum_{j=N_1+1}^{N_1+N_2} F_{2\perp i,j} I_j + \frac{1}{\rho_1}\sum_{j=N_1+N_2+1}^{N_1+2N_2} F_{1\perp i,j} I_j = 0 \ldots\ldots i = N_1+1, N_1+N_2 \qquad (B.4)$$

Where,

$$F_{a\perp i,j} = -\frac{\partial P_{aij}}{\partial z} = \frac{\rho_a}{4\pi}\left(\frac{(zz_i - zz_j)}{d^3} + \frac{(zz_i - zz'_j)}{d'^3}\right)$$

$$F_{1\perp i,j} = -\frac{\partial P_{1ij}}{\partial z} = \frac{\rho_1}{4\pi}\left(\frac{(zz_i - zz_j)}{d^3} + \frac{(zz_i - zz'_j)}{d'^3}\right)$$

$$F_{2\perp i,j} = -\frac{\partial P_{2ij}}{\partial z} = \frac{\rho_2}{4\pi}\left(\frac{(zz_i - zz_j)}{d^3} + \frac{(zz_i - zz'_j)}{d'^3}\right)$$

Where, $F_{\perp ij}$ expresses the field coefficient normal to the soil boundary at the contour points, and zz_i&zz_j are the dimension of the contour points and current sources in *z* direction respectively. Therefore, the current source values on the original grid can be determined by solving Eqs. (B1) to (B4).
The R_g can be calculated as follows;

$$R_g = \frac{V}{\sum_{j=1}^{N_1} I} \qquad (B.5)$$

Where, *V* is the reference *GPR* that applies to the grid and assumed to be 1V.
After computing the current values of the current sources, the voltage at any point xx on the earth's surface (Vxx) can be determined by computing the potential matrix ($P_{ax,j}$, $P_{1x,j}$ and $P_{2x,j}$) applying Eqn. (B1).

APPENDIX C: VERIFICATION OF THE ECM AND EIM

In [17], a validation of ECM were accomplishes comparing the results of the ECM according to grounding results with the results from Boundary element method (BEM) and the empirical formula that were addressed in [3]. On the other hand, a comparison between the ECM and BEM were carried out in some grid configuration with and without vertical rods to illustrate the adaptaion between the two methods for determining the ESP. Based on the grid and soil specifications for the following case, the comparison was explained as in Table C1, Fig. C1 and Fig. C2. The input data about the grid and soil specifications were;
Number of meshes (N) = 64, side length of the grid in X direction (X) = 75m, side length of the grid in Y direction (Y) = 75m, grid conductor radius = 5 mm, vertical rod length (Z) = 0 (no vertical rod), the depth of the grid (h) = 0.5 m, resistivity of the soil (ρ) = 2000 Ω.m and the permittivity of the soil is 9.
The following Table C1 explains that the result from the proposed method is close to the other formula in [3] and also the values of resistance that calculated by BEM[19].

TABLE C1: GROUNDING RESISTANCE BETWEEN THE BEM AND CSM AND THE OTHER FORMULAS THAT USED IN IEEE STANDARDS [3]

	R_g ohm	
	Without vertical rods	With vertical rods (2m)
	75m×75m	75m×75m
CSM	11.75	11.77
BEM [15]	12.6	12.5
Dwight [3]	11.81	11.8
Laurent [3]	13.29	13.23
Sverak [3]	13.23	13.16
Schwarz [3]	11.11	11.01

Figures C1 and C2 explained that the comparison between CSM and BEM for earth surface potential calculation. The Figures explained that the two methods were close to each other for calculating the ESP, although the two methods have different techniques.

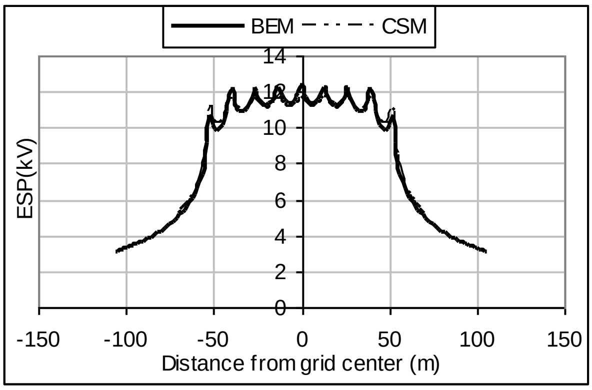

Fig. C1: Comparison between charge simulation method and Boundary Element Method for 64 meshes (75m*75m) grid without vertical rods (ρ=2000 Ω.m)

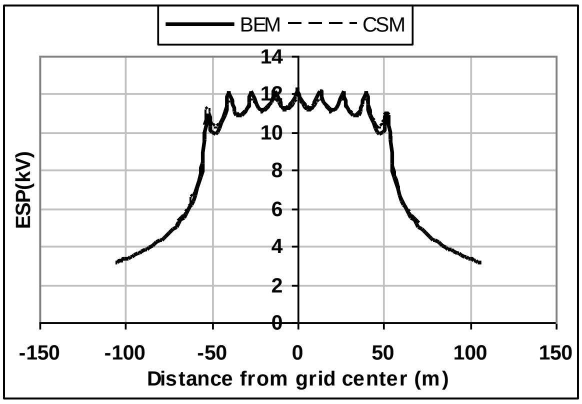

Fig. C2: Comparison between charge simulation method and Boundary Element Method for 64 meshes (75m*75m) grid with vertical rods 2m and (ρ=2000 Ω.m)

For two layer soil, the validation of the EIM was accomplished in [18], they carried out the same proposed technique as in [4] for some examples that were taken from [3], [20, 21]. They concluded that the optimal number of current sources taken in the studied cases ranged from 3000-4000. They compared the grounding resistance, touch and step voltages for the three examples in [3], [20, 21] and they concluded the ability of EIM to get an accurate value according to experimental, infinite series method (ISM) values and Electric Power Research Institute (EPRI).