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Optimization Technique for Grounding Grids Design

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Abstract — **A more accurate and practical method to calculate the Earth Surface Potential (ESP) is used. This method is Charge Simulation Method (CSM). A new application is proposed for getting the optimization design of the grounding grids. The basic design quantities of the grounding grids are the ground resistance (R_g), the ground potential rise (GPR), touch and step voltages and the design cost. These mentioned quantities depend on the grid parameters, which are its side lengths and vertical rod length. The dependence of the design quantities of the geometric parameters is given by field computation based on equivalent charges. The effect of number of point charges on the grids, the profile location, and the vertical rod length on ESP is studied. Numerical example is introduced to explain the performance of this method to give valuable information about the grid parameters that satisfy optimization.**

Index Terms — **Grounding grids, charge simulation method, and earth surface potential.**

I. INTRODUCTION

A Safe grounding design has two objectives: the first one is the ability to carry the electric currents into earth under normal and fault conditions without exceeding operating and equipment limits or adversely affecting continuity of service. The second is how this grounding system ensures that the person in the vicinity of grounded facilities is not exposed to the danger of electric shock.

To attain these targets, the equivalent electrical resistance (R_g) of the system must be low enough to assure that fault currents dissipate mainly through the grounding grid into the earth, while maximum potential difference between close points into the earth's surface must be kept under certain tolerances (step, touch, and mesh voltages)[1].

Computerized grounding analysis in uniform and two-layer soil types became widespread, mainly because of the enhanced accuracy, speed and flexibility afforded by the use of computers. Several publications [2-12] have discussed the analytical methods to calculate ESP and grounding resistance used when uniform and two-layer soils are involved. Many efforts have been made to measure the grounding resistance as well as the earth surface potential using scale model [13-18].

In the last decades, some intuitive techniques for grounding grid analysis such as the Average Potential Method (APM) have been developed. A new Boundary Element Approach has been recently presented [10, 11] that includes the above mentioned intuitive techniques as particular cases.

In this kind of formulation the unknown quantity is the leakage current density, while the potential at an arbitrary point and the equivalent resistance for grounding grids must be computed subsequently.

In the field of grounding systems design, the quality means that how these grounding systems safeguard those people that working or walking in the surroundings of the grounded installations, on the other hand

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minimizing the cost of design to satisfy optimization.[1]

In this paper, a Charge Simulation Method together with Image Method to compute the ESP is described. , the attractiveness of the method, when compared with the Finite Element and Finite Difference Method emanates from its simplicity in representing the equipotential surfaces of the electrodes, its application to unbounded arrangements whose boundaries extend to infinity and its direct determination to the electric field.

A new application is proposed for getting the optimum design of grounding systems. Effect of number of point charges on the grids, profile location, and vertical rod length on ESP is studied. The validation of the proposed method is explained by comparison between its results and IEEE standard [1] as well as the other method that use to calculate the earth surface potential such as Boundary Element Method [10, 11]. For the sake of simplicity, the soil is assumed to be homogeneous.

II. IMPROVED DESIGN OF GROUNDING GRIDS

The distribution of the Earth Surface Potential (ESP) helps us to determine the step and touch voltages, which are very important for human safe. The Charge Simulation Method to calculate the ESP is illustrated in Fig. 1.

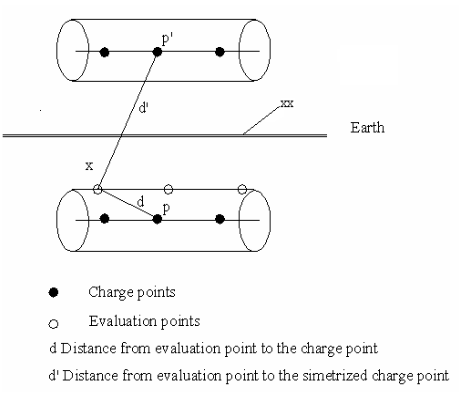


Fig. 1. Illustration of the charge simulation method to calculate Earth Surface Potential.

As in Fig. 1, the fictitious charges are taken into account in the simulation as point charges. The charges of the point charges will be known by applying 1 [19, 20];

$$\phi_i = \sum_{j=1}^{n} P_{ij} Q_j \tag{1}$$

where, d_{ij} is the distance between contour point i and charge point j and d'_{ij} is the distance between the contour point i and image charge point j' as shown in Fig. 1.

The position of each point charges and each contour point are determined in X, Y and Z coordinates where the distance between the contour (evaluation) points and the charge points are calculated as the following ;

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

where, d_{ij} is the distance between contour point i and charge point j and d'_{ij} is the distance between the contour point i and image charge point j' as shown in Fig. 1.

The position of each point charges and each contour point are determined in X, Y and Z coordinates where the distance between the contour (evaluation) points and the charge points are calculated as the following ;

$$\begin{aligned} d_{ij} &= \sqrt{(X_j - X_i)^2 + (Y_j - Y_i)^2 + (Z_j - Z_i)^2} \\ d'_{ij} &= \sqrt{(X'_j - X_i)^2 + (Y'_j - Y_i)^2 + (Z'_j - Z_i)^2} \end{aligned} \tag{3}$$

where, X_j, Y_j and Z_j are the dimensions of the point charge and X_i, Y_i and Z_i are the dimensions of the contour point.

After solving 1 by knowing the inverse matrix of P_{ij}, the magnitude of simulation charges is determined, as soon as an adequate charge system has been developed, the potential and field at any point xx outside the electrodes as shown in Fig. 1 can be calculated again by using the following equation;

$$\phi_{xx} = \sum_{j=1}^{n} P_{xxj} Q_j \qquad (4)$$

where, ϕ_{xx} is the voltage at the arbitrary point xx, P_{xxj} is the potential coefficient matrix for the point xx with all point charges and Q_j is the calculated point charges.

After knowing the charge at every point charge, the earth surface potential is calculated and also the duality expression is used to get the grid resistance from 4,

$$C = \frac{\sum_{j=1}^{n} Q_j}{V} \qquad (5)$$

$$R_g \times C = \rho \times \varepsilon$$

where, C is the capacitance of the grounding grid, V is the voltage applies on the grid and defined as 1 V, Q_j is the charge of point charge that used for the calculation, ρ is the soil resistivity and ε is the soil permittivity.

An illustration of grounding system to explain the design quantities of the grounding grids is presented as in Fig. 2.

Fig. 3 explains the quality model that used to introduce the optimization design of grounding grids. The tool box in Fig. 3 includes the equations which calculate the grounding resistance, earth surface potential (ESP), touch voltage, step voltage and the total cost of the design by using the proposed method that based on the equivalent charges. The flow chart in Fig. 4 explains how the algorithm is working, in the first; the calculation of the ESP, touch and step voltage and the cost of design is carried out. Therefore the initial quality factor which is based on the pervious quantities is calculated according to the objective function as described in Fig. 5. The algorithm starts to choose the random values for the grid dimensions with 10 next generations to get the best quality factor from new generations. Then, the algorithm compare between the initial value of the quality factor with the best value from the next generation to specify the grid dimensions that satisfy optimization case. The algorithm repeats this process until the search radius of the variation parameters are less than the limit condition which is 0.1 of the initial variation parameters.

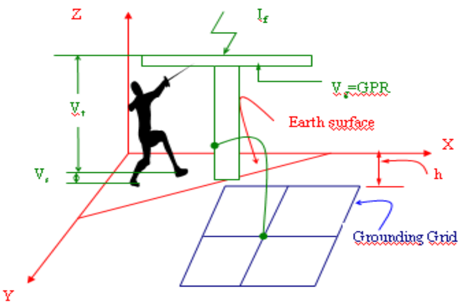


Fig. 2. Illustration of the grounding grid, step and touch voltage.

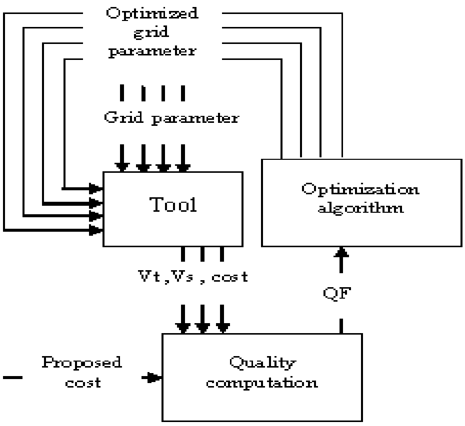


Fig. 3. Quality model for the optimum design of grounding grids.

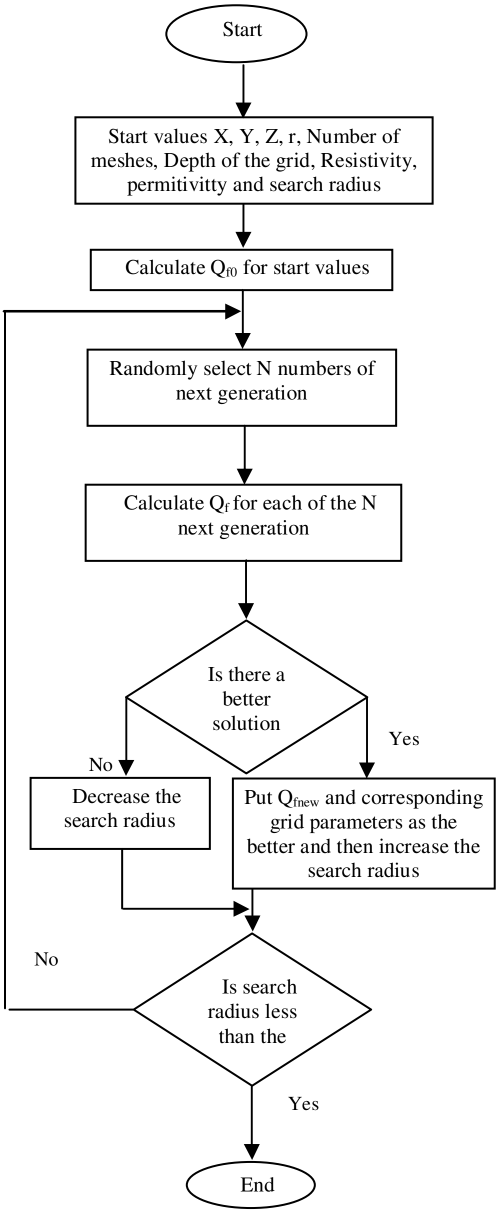
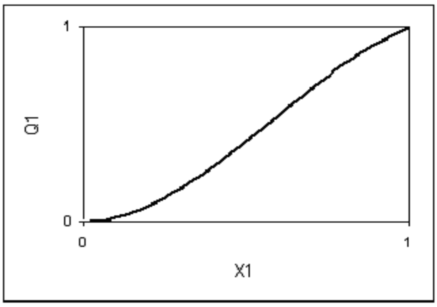


Fig. 4 Flow chart of the program based on Evolutionary Strategy to optimize the grounding grid design.

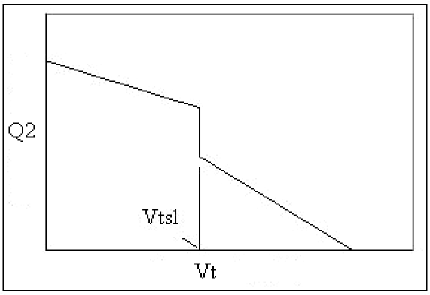
The results from the tool box in Fig. 3 compare with the safe limit value for touch voltage, step voltage and the cost at the same case to get the quality factor. Equation 6 explains that the quality factors depend on the grid parameters which are the grid side length and the length of the vertical rods.

$$\begin{aligned} Q_F &= f_1(Q_i),\ \ i=1,2,3 \\ Q_1 &= \begin{cases} f_2\left(proposed\cos t, \cos t\right) & \\ \qquad for \quad \text{proposed cost} > \cos t & \\ 0 \qquad for \quad \text{proposed cost} \le \cos t & \end{cases} \\ Q_2 &= f_3(V_{tsl}, V_t) \\ Q_3 &= f_4(V_{ssl}, V_s) \\ Cost, V_t, V_s &= f_5(X, Y, Z) \end{aligned} \tag{6}$$

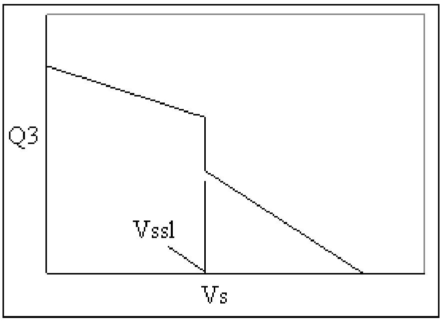
where, Q_F is the total quality factor, V_t, V_s are the calculated touch and step voltages, V_{tsl}, V_{ssl} are the safe limit of touch and step voltages at the case study, X is the side length of the grid in x direction, Y is the side length of the grid in y direction, Z is the length of the vertical rod if available and r is the grid conductor radius.



(a)



(b)



(c)

Fig. (5a, b, c). The relationships between the quality factors and (cost, V_t, V_s).

III. EARTH SURFACE POTENTIAL AT DIFFERENT CASES

The results from the proposed method are described in this section. The characteristics of the grid are 50*50 m^2, the radius of the grid rods (r) is 8 mm, the length of vertical rods (L_{vr}) is (3m), the radius of it (r_{vr}) is (5mm) , the grid depth (h) is 0.5 m, the resistivity of the soil (ρ) is 100 Ω.m.

The effect of some parameters on the earth surface potential is studied. Fig. 6 describes the effect of the number of point charges on the earth surface potential, the small change is observed when the number of point charges increases.

The profile which determines the location that the man stands above the grounding grid is very important to determine the touch and step voltages that the man exposes. It is seen from Fig. 7 that the man exposes to the dangerous touch voltage when he stands at the corner mesh of the grid.

In Fig. 8, the vertical rods 6m length are connected to the 4 meshes grid and from the results, the additional of vertical rods to the grid cause a reduction in the grid resistance and hence the earth surface potential decreases and then the touch voltage decreases. Also in Fig. 9, the vertical rod length has an effect on the earth surface potential, an increase in vertical rod length leads to reduction in ESP.

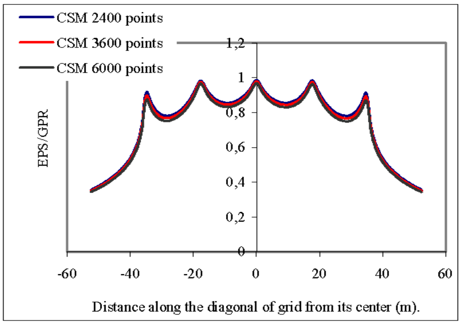


Fig. 6. The effect of number of point charges on the earth surface potential.

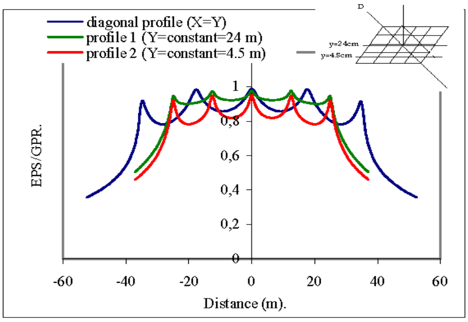


Fig. 7. The effect of profile location on the earth surface potential.

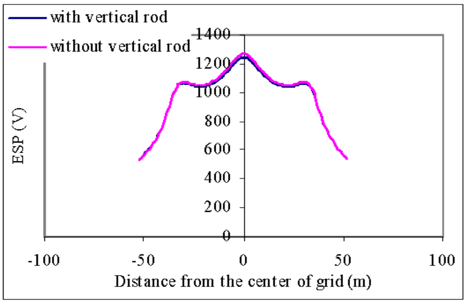


Fig. 8. Effect of vertical rod on the earth surface potential.

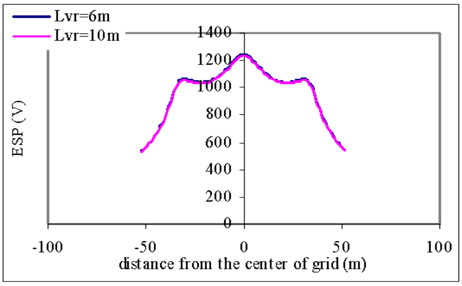


Fig. 9. Effect of vertical rod length on the earth surface potential.

IV. VALIDATION OF THE PROPOSED METHOD AND NUMERICAL EXAMPLE

To satisfy the validation of the method, the case of study is taken as the following, the input data about the grid configuration: Number of meshes (N) = 4, side length of the grid in x direction (X) = 70 m, side length of the grid in y direction (Y) = 70 m, grid conductor radius = 10 mm, vertical rod length (Z) = 0 (no vertical rod), depth of the grid (h) = 0.5 m, resistivity of the soil (r) = 100 ohm.m.

As shown in Table I a good agreement is observed between the value of grounding resistance of the case under consideration from the proposed method and the empirical formulas for IEEE Standard [1].

TABLE I
VALIDATION OF THE PROPOSED METHOD.

Formula	Resistance (Ω.m)
Dwight [1]	0.63286
Laurent [1]	0.87095
Sverak [1]	0.86708
Schwarz [1]	0.76099
Charge Simulation Method	0.7266

Figs. 10 and 11 explain that the proposed method satisfies an agreement with the other methods which use to calculate surface potential as the Boundary Element Method [10, 11].

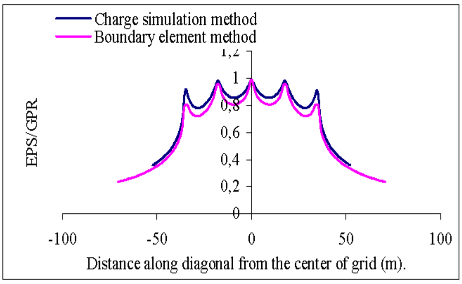


Fig. 10. Comparison between proposed method and Boundary Element Method [10,11] for 16 meshes grid without vertical rods.

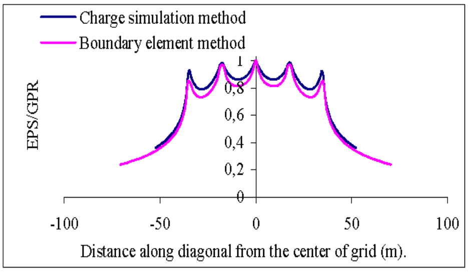


Fig. 11. Comparison between proposed method and Boundary Element Method [10,11] for 16 meshes grid with vertical rods (2m length).

The next numerical example is produced to explain the input and output data for the application and how this application helps us to give the optimum design of grounding grid that satisfies the safe condition for people that working or walking in the surroundings of the grounded installations and also good economical results.

Starting values of the grid configuration:

Number of meshes (N) = 4, side length of the grid in x direction (X) = 70 m, side length of the grid in y direction (Y) = 70 m, grid conductor radius = 10 mm, vertical rod length (Z) = 0 (no vertical rod), depth of the grid (h) = 0.5 m, resistivity of the soil (ρ) = 100 Ω.m, the threshold value of safe touch and step voltages are computed as in [1] and taking into account that the back up fault clearing time is 1 s with the soil resistivity 100 Ω.m uniform soil. The safe limit of the touch and step are V_{tsl} = 180 V and V_{ssl} = 251 V, the proposed cost is assumed 1000

Euro, the search radius is 0.25 of the variation parameters, the number of next generations is 10.

Table II shows the values of touch, step voltages and the cost at the starting of the design and after using the optimization algorithm.

TABLE II
TABLE II COST, TOUCH AND STEP VOLTAGES FOR 4 MESHES GRID

	V_t (V)	V_s (V)	Cost (Euro)	Dimension for 4 meshes grid
Starting design	242.7	123.4	332	70*70 m^2
Optimized design	25.8	47	494	235.65*75.89 m^2

The cost of the optimized design is higher than at starting design but is still lower than the proposed cost. The very important issue for the optimization that the touch and step voltage must be lower than the safe limit value. From the table the optimization algorithm able to decrease the touch and step and keep the cost lower than the proposed cost.

As in [2] the radius of the conductor of the grid has very small effect on the Earth Surface Potential as well as on the touch and step voltage, therefore the radius of the conductor is constant at the processing of the optimization.

V. CONCLUSIONS

The paper aims to explain a more accurate and practical technique which can be used to calculate the Earth Surface Potential due to discharging current into grounding grid. This technique depends on the Charge Simulation Method. An important advantage of CSM is the high accuracy of electric field calculations which can be achieved without large computational effort. The proposed method gives a good agreement with the IEEE standard empirical formulas and the other method which uses to calculate the ESP such as Boundary Element Method.

In the field of grounding systems design, the optimization means that how these grounding systems not only safeguard those people that working or walking in the surroundings of the grounded installations, but also minimize the cost of design.

The use of an Evolutionary Computation (EC) technique for the optimization of a grid design algorithm allows for the attainment of optimal fitness (i.e. the best choice of parameter values) through an automated process.

REFERENCES

[1] IEEE Guide for safety in AC substation grounding, IEEE Std.80-2000.

[2] F. P. Dawalibi, D. Mukhedkar "Parametric analysis of grounding grids" *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-98, No. 5, pp. 1659-1667, Sep/Oct 1979.

[3] J. G. Sverak, “Simplified analysis of electrical gradients above a ground grid, part I- how good is the present IEEE method?,” *IEEE Trans. on Power Apparatus and Systems,* vol. pas-103, pp. 7-25, Jul. 1984.

[4] J. M. Nahman, V. B. Djordjevic, “Nonuniformity correction factors for maximum mesh and step voltages of ground grids and combined ground electrodes,” *IEEE Trans. Power Delivery*, vol. 10, no. 3, pp. 1263-1269, Jul. 1995.

[5] B. Thapar, V. Gerez, A. Balakrishnan, and D. A. Blank, “Simplified equations for mesh and step voltages in an AC substation,” *IEEE Trans. Power Delivery.*, vol. 6, no. 2, pp. 601-607, Apr. 1991.

[6] R. J. Heppe, “Computation of potential surface above an energized grid or other electrode, allowing for non/uniform current distribution”, *IEEE Transactions on Power Apparatus and Systems,* Vol. Pas-98, No. 6, Nov/Dec 1978.

[7] J. Nahman, and S. S Kuletich, “Irregularity correction factors for mesh and step voltages of grounding grids”, *IEEE Transactions on Power Apparatus and Systems,* Vol. Pas-99, No. 1, pp. 174-179, Jan/Feb: 1980.

[8] Cheng-Nan Chang, Chien-Hsing Lee, “Computation of ground resistances and assessment of ground grid safety at 161/23.9 kV indoor/type substation”, *IEEE Transactions on Power Delivery,* Vol. 21, No. 3, pp. 1250/1260, July 2006.

[9] J. A. Güemes, F. E. Hernando “Method for calculating the ground resistance of grounding grids using FEM,” *IEEE Transaction on power delivery,* vol. 19, No. 2, April 2004, pp 595-600.

[10] F. Navarrina, I. Colominas, “Why Do Computer Methods for Grounding Analysis Produce Anomalous Results?,” *IEEE Transaction on power delivery,* vol. 18, No. 4, October 2003, pp 1192-1201.

[11] I. Colominas, F. Navarrina, M. Casteleiro, "A Numerical Formulation for Grounding Analysis in Stratified Soils", *IEEE Transactions on Power Delivery,* vol. 17, April 2002, pp 587-595.

[12] E. Bendito, A. Carmona, A. M. Encinas and M. J. Jimenez “The extremal charges method in grounding grid design,” *IEEE Transaction on power delivery,* vol. 19, No. 1, pp 118-123, January 2004.

[13] R. Caldecott, D. G. Kasten, “Scale model studies of station grounding grids,” *IEEE Trans. Power Apparatus and Systems,* Vol. PAS-102, no. 3, pp. 558-566, 1983.

[14] B. Thapar, S. L. Goyal, “Scale model studies of grounding grids in non-uniform soils,” *IEEE Transactions on Power Delivery,* Vol. PWRD-2, no. 4, pp. 1060-1066 , 1987.

[15] C. S. Choi, H. K. Kim, H. J. Gil, W. K. Han, and K. Y. Lee, “The potential gradient of ground surface according to shapes of mesh grid grounding electrode using reduced scale model,” *IEEJ Trans. On Power and Energy,* Vol. 125, no. 12, pp. 1170, 2005.

[16] B. Thapar, K. K. Puri, “Mesh Potential in high voltage station grounding grids”, *IEEE Transaction on Power Apparatus and Systems,* Vol. Pas-86, pp. 249-254, 1967.

[17] A. Elmorshedy, A. G. Zeitoun, and M. M. Ghourab, “Modelling of substation grounding grids,” *IEE Proceedings,* Vol. 133, Pr. C, No. 5, July 1986.

[18] I. F. Gonos, “Experimental study of transient behavior of grounding grids using scale model”, *Measurement Science and Technology.* 17 (2006), pp. 2022-2026.

[19] N. H. Malik, “A review of charge simulation method and its application,” *IEEE Transaction on Electrical Insulation,* vol. 24, No. 1, pp 3-20, February 1989.

[20] H. Singer, H. Steinbigler and P. Weiss. A charge simulation method for the calculation of high voltage fields. *Trans. IEEE* PAS 93 (1974), pp. 1660–1668.

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